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Development of Direct Reading Thickness Gauge for Lead Equivalent Thickness Measurement of Personnel Protective Equipment

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***Abstract*—Measurement of lead equivalent thickness of personal protective equipment (PPE) is important to carry out at least at the commissioning stage in order to verify the compliance of the equipment with the standard regulations of Malaysian Standard (MS) 838, IAEA Safety Series No.115 and IEC 61331. In this study, a gauge for measuring lead equivalent thickness of PPEs such as lead apron, thyroid shield, ovary shield and gonad shield was designed and fabricated. The gauge consists of supporting frame to accommodate a ^{241}Am radioactive source, scintillation detector and PPEs; and a survey meter connected to Ludlum software for data logging. The standard calibration curve for estimating the lead equivalent thickness of PPEs was established using ^{241}Am radioactive source. The curve was determined based on the most reliable results acquired from various measurements set-up including multiple sizes of collimator and different source-detector distance (SDD) for the lead thickness from 0 mm to 5 mm. In this work, the standard calibration curve obtained for the collimator size of 0.5 mm diameter and SDD of 50 cm is chosen. As a conclusion, development of lead equivalent thickness gauge was accomplished and it can be used for measuring the thickness of PPEs used in the diagnostic radiology energies ranges in Malaysia.**

***Keywords*—lead equivalent thickness, personal protective equipment, thickness gauge**

I. Introduction

Most medical regulations specify the thickness of radiation protective barriers and clothing supplied for the protection of staffs and patients in term of lead equivalent thickness [3,4,5,6,8]. In order to ensure compliance with the requirements of the regulation, the thicknesses of these shielding materials have to be verified at least during commissioning stage [1]. Some protective barriers may subject to ageing and becoming ineffective after sometimes. Improper storage or rough handling may damage or crack the lead in personal protective equipment (PPE) which demands more regular check on the integrity of the PPEs [2,7,10,11].

In Malaysia, all public and private hospitals including medical centers and clinics are required to provide appropriate PPEs with sufficient lead equivalent thickness for their staffs and patients when dealing with ionizing radiation to satisfy the principles of optimization of dose. The most common PPE is lead apron which is considered necessary for general diagnostic radiography works. For interventional radiological procedures, additional PPEs such as thyroid shield, goggle, lead curtain, lead glass and lead skirt may be required for the staffs especially for cardiologists and radiologist whereas gonad shield or ovary shield and other protective shielding may be required for the radiation protection of patients.

Therefore, it is worth to design the thickness gauge for measurement of the effective thickness of radiation protective barriers including wall for an X-ray room and clothing. However, in this study, the scope of work is limited to cater only for personal protective clothing such as lead apron, thyroid shield, lead glove and gonad shield. This study includes design and fabrication of the gauge, interfacing detector with computer, data input, establishing a software for data analysis and establishment of standard calibration data.

The measurement of lead (Pb) equivalent thickness using a gamma emitter of ^{241}Am source (59 keV) is a common technique in diagnostic radiology but up to date, this measurements were performed manually. Development of the thickness gauge to provide a direct reading of lead equivalent thickness is considered new technological innovation in the field. The aim of this study is to establish a computer controlled thickness gauge for measurement of lead equivalent thickness incorporating into personal protective clothing such as lead apron, thyroid shield and gonad shield.

II. Materials and Method

A. *Designing and Fabricating of Lead Equivalent Thickness Gauge*

The lead equivalent thickness gauge consists of a supporting frame for accommodating a radiation detector, lead filters, PPE and ^{241}Am radioactive source. There are two types of material use in fabricating the gauge: (i) stainless steel for the supporting frame; and (ii) lead for the compartments of source and detector. The stainless steel was chosen due to light weight, corrosion proof, easy for cleaning and to protect

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operator from contact with a toxic lead. The lead is functioned: (i) as a shielding to protect the operator from the gamma radiation source; and (ii) to minimize the background radiation counted by the detector.

The frame was designed to place a Ludlum scintillation detector, model 44-71 with external dimension of 6.7 cm x 22.9 cm (diameter x length) and 0.7 kg weight. This detector is made of 5.1 cm diameter and 2 mm thick of Thallium-activated Sodium Iodide (NaI(TI)) flat face crystal and having an active area of 17.8 cm^2. For reducing the background radiation, the detector was shielded with 0.5 cm lead in the 0.2 cm well drilled of stainless steel. The detector was connected to a Ludlum survey meter, model 2241 (Ludlum Measurements Inc., USA). The survey meter then was connected to a data logger, model 224x versions 1.0.0 for display and controls the measurements (Ludlum Measurements Inc., USA). For data counting, the survey meter was set to RS-232 data dump mode. The data is displayed in measurement unit of count per minute (cpm). The detector compartment was designed to ensure the detector was placed at the central axis of the beam and horizontally aligned with the radiation beam.

The source compartment was designed to accommodate a ^{241}Am source, type OB 875/1.05/875 (Buchler GmBh, Germany). It is located in opposite site of the detector compartment. The ^{241}Am source was used in this study due to its corresponding energy with the photon energy produced by the general X-ray machine for the maximum tube potential of 150 kV. The source strength is 7.4 GBq. For radiation protection purpose, the source was placed in 4 cm lead shielding in drilled well stainless steel with 0.5 cm thickness to avoid exposure of gamma radiation to operator.

Slot for filters and PPE was placed in between of detector and source compartments; and at fixed distance of 8 cm from the detector. The slot was fabricated so that the filters and PPE can be positioned vertically with the radiation beam. Distortion in positioning the filters with the radiation beam may result to establishment of inaccurate calibration curve thus affecting the result of lead equivalent thickness of PPEs. This is due to change of actual thickness of filters when the filters were not in perpendicular positioning with the radiation beam. The gauge also was equipped with a set of 2 cm thickness of beam collimator consists of 0.5 cm, 1.0 cm and 1.5 cm diameter collimators. The collimators were placed close to detector to minimize scatter radiations. These collimators can be changed if the adjustment of the beam field size is required. Estimated beam size at detector for 20 cm, 30 cm, 40 cm and 50 cm was calculated as shown in Table 1. A shutter with 0.5 cm thickness and 3.0 cm diameter is functioned to control the radiation exposure either 'ON' or 'OFF'. Both the collimators and shutter were made of lead.

The supporting frame was placed on the 30 cm x 100 cm (wide x length) base. At the base, a straight rail was designed so that the distance between source and detector can be adjusted to cater distance between 20 cm to 50 cm. In order to minimize the uncertainty of measurement, the source compartment is set at fixed position while the detector compartment together with a filter slot is movable.

B. *Establishing the Standard Calibration Curve*

Two parameters were manipulated in order to obtain the standard calibration curve for this thickness gauge: (i) size of collimator from 0.5 - 2 cm Ø; and (ii) source-detector distance from 20 - 50 cm. Readings of count rate for five thicknesses of lead with 0 mm (without filtration), 0.106 mm, 0.325 mm, 0.432 mm and 0.539 mm were obtained. The counting time was set to 60 s. An average count rate from 10 readings minus the background radiation was calculated to obtain net count rate. The standard uncertainty was calculated based on the count rate standard deviation. Average reading for each thickness then was normalized to initial reading (without filtration). A graph of normalized reading against lead thickness was plotted as shown in Fig. 2 and Fig. 3. Exponential equations and determination coefficients (R^2) for the graphs were determined.

III. Results and Discussion

A. *Lead Equivalent Thickness Gauge*

The lead equivalent thickness gauge was developed and ready to be used for establishing the standard calibration curve and then for measuring thickness of PPEs. Fig. 1 shows a complete set of the gauge that consists of source compartment, filter/PPE slot, detector compartment, a survey meter and laptop with Ludlum software for data acquisition. For the radiation safety, the operator was recommended to keep a laptop at least at 1 m distance from the source compartment during the measurement. There is no leakage of radiation source was recorded at the surface of source compartment. The operator also was reminded to always close the shutter before setting the filters or PPEs at the filter/PPE slot. The radiation exposure at filter slot is 3.3 ± 0.1 mR/hr and 10 ± 2 μR/hr when shutter open and shutter close, respectively.

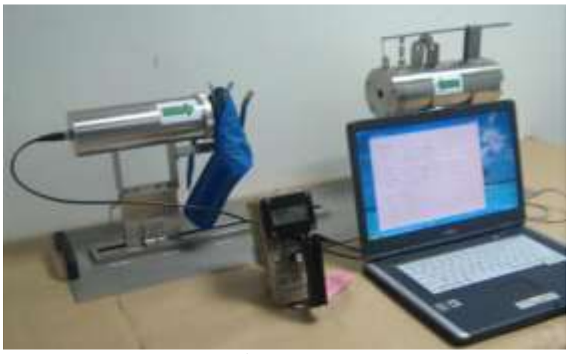

Fig. 1. A complete system of lead equivalent thickness gauge.

B. *Estimation of Beam Size and Detector Surface*

The beam size at the detector surface for 20 cm, 30 cm, 40 cm and 50 cm SDD was calculated. The results were compared with the measurement carried out using an X-ray film. Estimation of field size is important in order to confirm the suitable size of collimator is chosen as well as to ensure the radiation beam was not exceeded the detector's active area during measurements. This is to minimize the production of scattered radiations that may affect the accuracy of measurement. Results of field size for different SDD are shown in Table 1. The field size at 20 cm SDD is taken as reference size. From Table 1, the relative percentage deviation between measured and calculated beam size for other SDDs is 6.25%. The measured and calculated beam sizes are exceeded the diameter of detector which is 4.76 cm. Therefore, adequate thickness of beam collimators were fabricated to filtered out all radiation exposures when the measurement is carried out at 40 cm and 50 cm SDD.

TABLE 1. COMPARISON OF BEAM SIZE FOR DIFFERENT SOURCE-DETECTOR DISTANCE.

Source-detector distance (cm)	Field size at detector surface (cm Ø)		Relative deviation, %
	Measured	*Calculated*	
20	3.2	3.2	0.00
30	4.5	4.8	6.25
40	6.0	6.4	6.25
50	7.5	8.0	6.25

C. The Standard Calibration Curve

The results of standard calibration curves for 0.5, 1.0 and 1.5 cm Ø collimator diameters are shown in Figure 2. The normalized reading is a ratio of count rate for each lead thickness to the initial counts rate without filtration. The data were fitted with an exponential line and serve as a guide for the eye. The graph shows that the collimator size of 1.5 cm Ø give the highest variation of normalized readings between 20, 30, 40 and 50 cm SDD, followed then by the collimator size of 1.0 cm Ø. The smallest variation of normalized readings is given by collimator size of 0.5 cm Ø. This condition may be contributed by higher scattered radiation when larger collimator size is used. As compared with the smaller collimators, the results show more stable and reproducible of normalized readings although the SDD is changed. From Fig. 2, we can conclude that the 0.5 cm Ø collimator provides the most reliable measurement of count rate for SDD between 20 cm to 50 cm.

Figure 3 shows the results of calibration curves for various distances between source and detector from 20 cm to 50 cm. The normalized reading is a ratio of count rate for each lead thickness to the initial counts rate without filtration. The data were fitted with an exponential line and serve as a guide for the eye. Each graph demonstrates that the existing of some deviations of normalized reading when different types of collimator are used in the measurement. It shows that the distance between source and detector has an effect on count rate; the further distance between source and detector the larger the variation of normalized reading. The biggest variation is shows by the measurement at 20 cm SDD, followed then by 30 cm SDD and 40 cm SDD. The smallest variation is given for the measurement at 50 cm SDD. These results may be due to decrease of scattered radiation to the detector since the source strength is weak. From these graphs, we can conclude that the SDD of 50 cm provides the most reliable readings in the measurement of count rate.

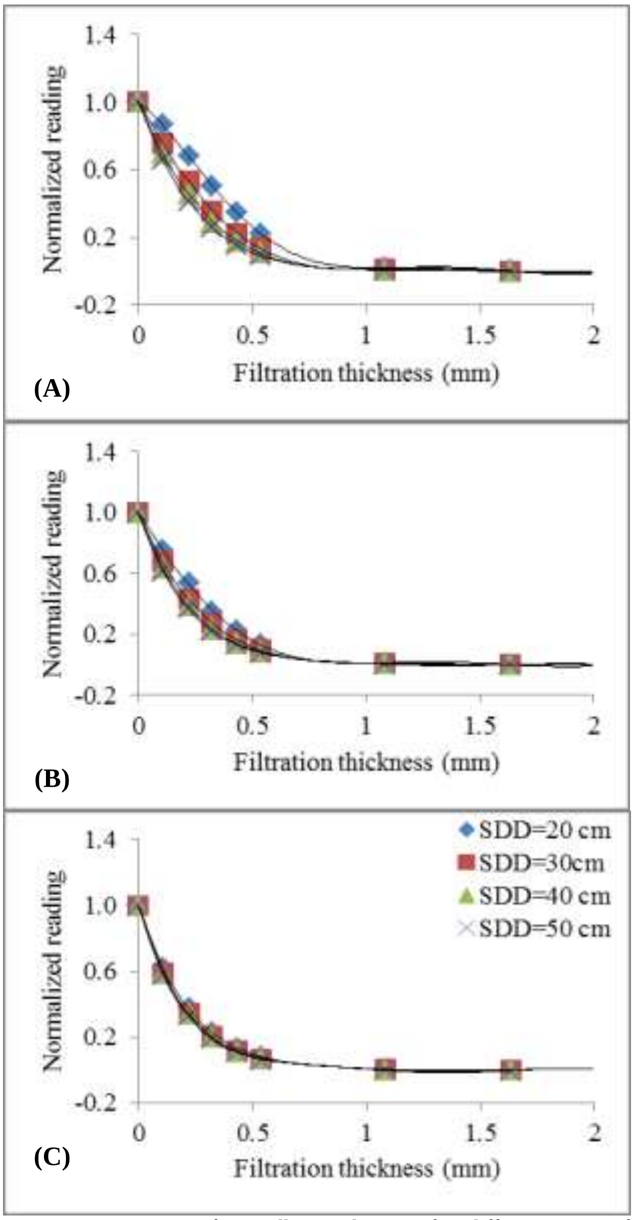

Figure 2. Response of scintillation detector for different sizes of collimator. (A) 1.5 cm Ø collimator. (B) 1.0 cm Ø collimator. (C) 0.5 cm Ø collimator.

From Figure 2 and Figure 3, the graphs show that the reading of normalization is started to reach background radiation level after being filtered with 0.6 mm of lead thickness. This condition means that radiation exposure from the ^{241}Am source with gamma energy of 59 keV could be completely shielded using this thickness of lead. It shows that the gauge can only be used to estimate the lead equivalent thickness of PPEs until maximum thickness of 0.6 mm Pb.

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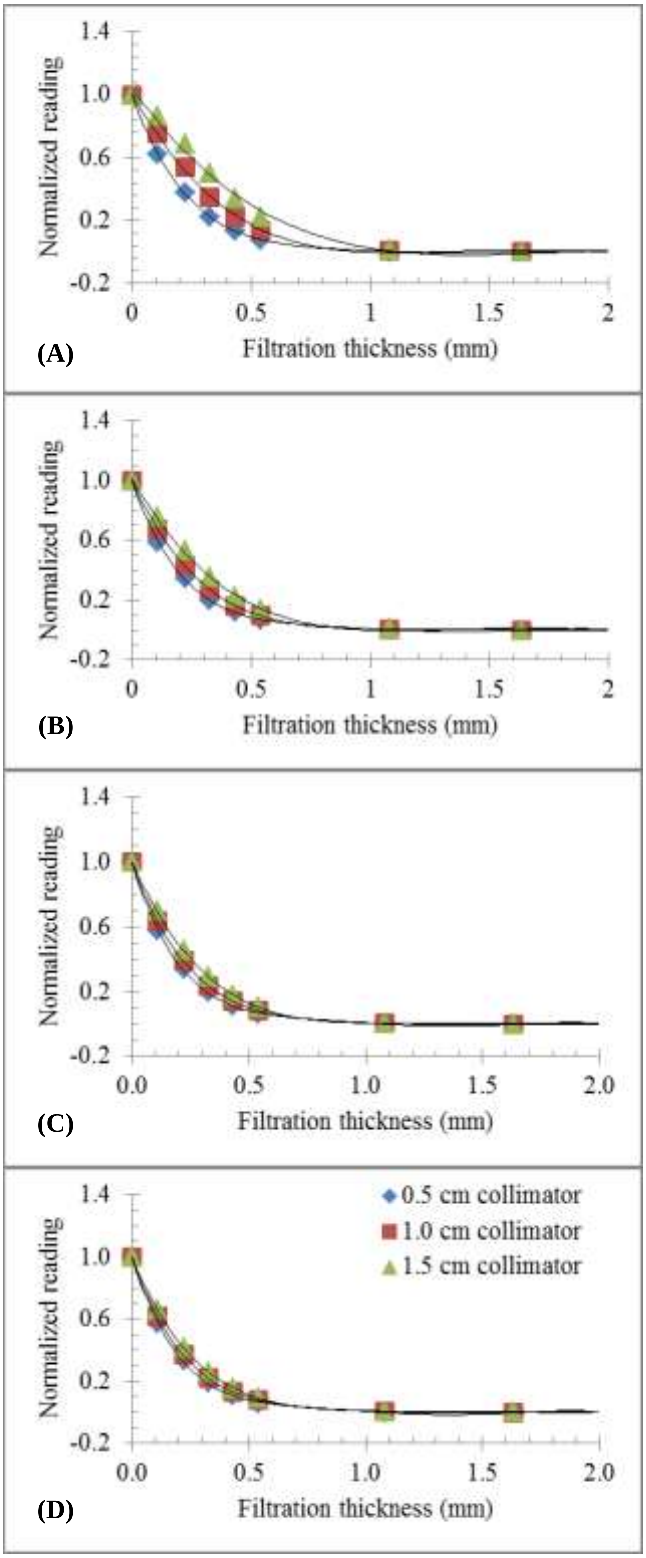

Figure 3. Response of scintillation detector for various distances between source and detector. (A) 20 cm SDD. (B) 30 cm SDD. (C) 40 cm SDD. (D) 50 cm SDD.

Figure 4 shows the standard calibration curve that was obtained from 0.5 cm diameter collimator and 50 cm SDD for total thickness of 0.539 cm. The count rate for each lead normalized reading and lead thickness with determination coefficient, R^2 of 0.9994. The normalized reading is a ratio of count rate for each lead thickness to the initial counts rate without filtration. The data were fitted with an exponential line. The graph shows that there is a very good agreement between exponentially proportional with lead thickness with gradient of 1.0165 mm^{-1}. The exponential equation between normalized reading and lead thickness obtained from Figure 4 is used in determining the lead equivalent thickness of PPEs. The equation also was used in the Matlab software that was developed to give a direct reading of lead equivalent thickness gauge [9].

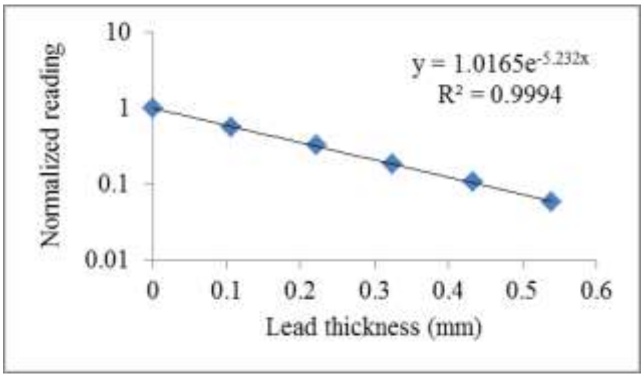

Figure 4. Standard calibration curve for 0.5cm Ø collimator and 50cm SDD.

D. *Verification of Standard Calibration Curve*

The standard calibration curve was verified by measuring the lead equivalent thickness of PPEs such as lead apron, thyroid shield, ovary shield and gonad shield belongs to Medical Physics Group, Malaysian Nuclear Agency. These PPEs are used for radiation protection to workers and patients in diagnostic radiology. From manufacturer's specification, the lead equivalent thicknesses of these PPEs are 0.5 mm Pb. The results of measurements of lead equivalent thickness of these PPEs are shown in Table 2. It shows that lead equivalent thicknesses of the PPEs are complied with the specification as stated by the manufacturer. The results of manufacturer stated lead equivalent thickness and measured lead equivalent thickness using thickness gauge were compared. The minimum relative deviation of 8% is given by ovary shield while the maximum relative deviation of 26% is given by lead glove.

E. *Advantages of Lead Equivalent Thickness Gauge*

The feasibility of using the lead equivalent thickness gauge was compared with the conventional technique used for estimating the lead thickness within PPEs by the hospitals and clinics. Table 3 shows the advantages of the lead equivalent thickness gauge in carry out the lead equivalent thickness measurements. From Table 3, the technique for the lead thickness measurement was improved by using the gauge such as reduction in measurement time, better accuracy of measurement and user friendly. The gauge is also portable so it can be easily transported for on-site measurement in the hospital or clinic in Malaysia.

TABLE 2. MEASUREMENTS OF LEAD EQUIVALENT THICKNESS OF PPEs USED IN DIAGNOSTIC RADIOLOGY.

Personnel Protective Clothing	Stated Lead Equivalent Thickness (mmPb)	Measured Lead Equivalent Thickness (mmPb)	Relative deviation (%)
Lead apron	0.5	0.61	22
Thyroid shield	0.5	0.56	12
Ovary shield	0.5	0.54	8
Gonad shield	0.5	0.56	12
Lead goggle	0.5	0.61	22
Lead glove	0.5	0.63	26

TABLE 3. COMPARISON THE LEAD EQUIVALENT THICKNESS GAUGE WITH THE CONVENTIONAL METHOD USED TO MEASURE LEAD THICKNESS IN PPEs.

Criteria	Conventional technique	Thickness gauge
Method of measurement	Indirect reading	Direct reading
Measurement time	2 hours	60 sec
Accuracy of measurement	± 1mm	± 0.01mm
User friendly	Require expert advise	Simple
Mobility	Fixed set up	Portable
Measurement technique	In standard laboratory	On site

IV. Conclusions

The first direct reading lead equivalent thickness gauge in Malaysia has been successfully developed. The gauge is now ready to be used for determining the lead equivalent thickness of personal protective equipment (PPEs) used in the diagnostic radiology field. As compared with the conventional technique, the gauge found to provide better practicality to users and gives better accuracy in measurements of lead equivalent thickness of PPEs. For future improvements, the standard calibration curves for various ranges of gamma energy such as for mammography, dental and computed tomography (CT) will be established. Therefore, users will get better confidence in terms of accuracy in the measurement of related PPEs.

Acknowledgments

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