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Establishment of Paraffix Wax Compound and NaCl as Soft-tissue Equivalent Material for Phantom Fabrication

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A phantom is a physical object or mathematical model used to mimic the properties of interactions of the human's tissues, absorption and scattering of radiation in radiation field. A physical phantom is made of tissue substitute of any material that has the same characteristics for ionising interaction. Commercial phantom materials are expensive and have a basic geometrical shape. Thus, there is a need to explore the potential of other cost-effective material for phantom fabrication in medical imaging. The main goal of this study was to establish a paraffin wax compound and NaCl as soft-tissue equivalent material for phantom fabrication. Nine samples with different paraffin-to-NaCI ratio were prepared. The attenuation coefficient of each sample was evaluated within gamma energy range of 88 keV and 1.33 MeV. The measurement of mass attenuation coefficients were performed with a NaI(Tl) detector in a gamma spectroscopy. Experimental results of attenuation coefficients were compared with XCOM software and ICRU Report 44. Results from these findings show that a combination of 75% of paraffix wax and 25% of NaCl is the best composition to mimic soft-tissue equivalent material, while, a combination of 60% of paraffin wax and 40% of NaCl is suitable for bone equivalent material.

Keywords: tissue equivalent material; total mass attenuation; bone equivalent material; phantom material; spectroscopy

I. INTRODUCTION

Studies on tissue equivalent materials for anthropomorphic phantom fabrication are important for radiation dosimetry and calibration in medical imaging (Naderi *et al*, 2015). These tissue-equivalent materials are fabricated from several chemical materials (Hasanzadeh and Abedelahi, 2011) and they have similar interaction of ionizing radiation to human tissue. The attenuation properties of phantom material must be as close as possible to those experienced by the irradiated tissue under similar conditions. Understanding on the physical properties of tissue equivalent materials and radiation interaction parameters are important to establish tissue-equivalent materials (Ferreira *et al.*, 2010).

At present, different type of materials were used to replicate human tissue and organs to measure the doses of ionizing radiation received by patients. These materials are known as tissue equivalent materials. These materials are widely used in medical physics area including diagnostic radiology, nuclear medicine and therapeutic radiology (Jones *et al.,* 2003; Amini *et al.,* 2018; Yemby Huamani *et al.,* 2019).

Polyethylene has been used as tissue equivalent material in medical imaging (Followill, 2014; Hasanzadeh and Abedelahi, 2011). However, polyethylene is expensive, has high potential of stress cracking and difficult to bond. Jones *et al.,* have fabricated tissue-equivalent materials for simulating the soft, lung and bone tissue of newborn, children and adult patients for CT examination procedures. These materials were compared with the reference materials found in ICRU report 44 (Jones *et al.*, 2003).

The ICRU report 44 has compiled a result of various studies on radiation interaction properties of tissue equivalent materials with ionizing radiation. The report presents the total mass attenuation coefficients and

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other quantities of tissues substitutes in radiation dosimetry and measurement for X-ray energy ranging from 1 keV to 50 MeV (White *et al.,* 1989; ICRU 1989).

Other materials that are often used as soft tissue-equivalent are bolus, nylon®, orange articulation wax, red articulation wax, PMMA, modelling clay, bee wax and paraffin (Ferreira *et al.* 2010). The study was performed to validate the best tissue-equivalent material to simulate human cerebral tissue, in terms of total mass attenuation coefficient and mass density in the energy range of 10 to 150 keV. Results were compared with established values established by International Commission on Radiation Units and Measurements – ICRU, report 44 and International Commission on Radiation Protection – ICRP, report 89 (White et al., 1989; Valentin *et al,* 2002).

Acrylic is also commonly used for tissue-equivalent materials. Ferreira *et. al.* (2010) constructed an anthropomorphic liver phantom in tomography hepatic procedures for quality control and improvement professionals in nuclear medicine. The phantom used self-polymerising JET classic, acrylic (Ferreira *et al.*, 2010).

Mass attenuation coefficient is defined as the measure of a material's ability to absorb or scatter electromagnetic radiation in any per unit of mass. The total mass attenuation coefficient was calculated through the photon energy and constituent elements of the material (Hubbell, 2006; Sidhu *et al*, 2012). Linear attenuation coefficient describes the fraction of a beam of X-rays or gamma rays that is absorbed or scattered per unit thickness of the absorber. Beer-Lambert Law is used to measure gamma ray attenuation coefficient by employing standard transmission method with narrow beam geometry (Singh *et al.*, 2015).

In this study, the mass attenuation coefficients of composite materials, paraffin wax and NaCl samples were determined at different gamma energies. In addition, Berger and Hubbell (1987/1999) also developed XCOM database to evaluate the cross-sections and attenuation coefficient of any element, compound or mixture. The ICRU Report 44 has compiled the results of various studies on utilization of tissue equivalent materials in diagnostic and radiotherapy applications. The ICRU Report 44 provides total mass attenuation coefficients and other quantities, calculated in X-ray energy range of 1 keV to 50 MeV (Jones *et al*, 2003).

II. MATERIALS AND METHODS

A. Preparation of samples

Eight samples of combination paraffin wax and NaCl were prepared in this study. The samples were denoted by samples A to F. These samples were prepared to mimic human soft tissue, while another three samples (G-I) were prepared to mimic bone tissue. The size of samples is 3 cm x 3 cm x 0.5 cm. Each sample has variety amount of NaCl and paraffin wax. Table 1 shows the percentage amount of NaCl in each sample.

Table 1. Percentage of NaCl in each sample.

Sample	Percentage of NaCl (%)
A	0
B	10
C	20
D	25
E	30
F	40
G	50
H	60
I	70

B. Linear attenuation coefficients of paraffin wax and NaCl

Linear attenuation coefficients of paraffin wax and NaCl compositions were evaluated within energy range of 87.83 keV and 1.33 MeV. These energies were chosen to represent energy range used in diagnostic imaging and nuclear medicine. The measurements were performed by using gamma spectroscopy scintillation system.

The scintillation system consists of NaI (Tl) detector, a photomultiplier tube, multichannel analyzer (MCA) and power supply. The NaI (Tl) detector was shielded with a lead housing to reduce scattered radiation. The samples were placed between detector and radiation source. The time was set for 6000 seconds.

The photo peak, full width at half maximum (FWHM) and net area of photo peak were measured using Meastro software. The radioactive sources used in this study were Am-241 (87.83 keV), Na-22 (1274.53 keV), Cs-137 (661.66 keV), Mn-54 (834.85 keV) and Co-60 (1173.24 keV and 1332.5 keV) to evaluate the attenuation coefficients of each sample. Figure 1 shows the result of spectrum obtained from MEASTRO software for Am-241.

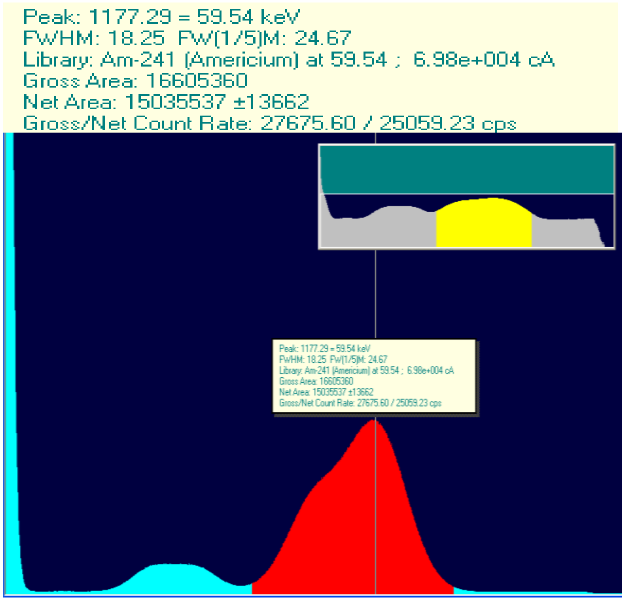

Figure 1. The Am-241 spectrum obtained from gamma spectroscopy system.

C. *The mass attenuation coefficients of samples*

The ability of a material to transmit or attenuate radiation is quantified by its mass attenuation coefficient. The mass attenuation coefficient for all samples was generated using Beer-Lambert's formula as stated in Eq. 1:

$$I = I_o e^{-\mu x} \quad (1)$$

I = emerging intensity

I_O = incident intensity

μ = linear attenuation coefficient (cm^{-1})

x = thickness of sample

The mass attenuation coefficients obtained from this experiment were compared with mass attenuation coefficients generated by XCOM software. The relative percentage difference between experimental and theoretical mass attenuation values of all samples was evaluated. The mass attenuation of samples A to I were compared with mass attenuation coefficient of human soft tissue and human bone from ICRU Report 44.

III. RESULTS AND DISCUSSION

The paraffin wax and NaCl introduced in this study is a core mixture of compound to represent the human soft tissue and human bone tissue. By adding NaCl to paraffin wax, the density of these materials increases based on the percentage amount of NaCl. The theoretical and experimental mass attenuation coefficients of paraffin wax and NaCl were compared at photon energies of 87.83 keV up to 1332.50 keV (Table 2).

Linear attenuation coefficient of paraffin wax and NaCl were evaluated by using gamma spectroscopy. The mass attenuation coefficients were calculated from Beer-Lambert's formula. The theoretical values were calculated using mixture rule from XCOM (Berger and Hubbell, 1987/1999).

Tables 2 and 3 show the mass attenuation coefficients of paraffin wax and NaCl. Results obtained from this study were in good agreement with theoretical results obtained from XCOM for energy ranging from 662 keV to 1332.5 keV. The percentage difference of mass attenuation coefficients between experimental and theoretical values are less than 5%.

This result suggested that the implementation of paraffin wax and NaCl as tissue equivalent material is suitable for therapeutic and nuclear medicine use. Small value of standard deviation, variance and mean of the samples were shown in Table 3.

The mass attenuation coefficient of samples A to F were compared with mass attenuation coefficient of human soft tissue based on ICRU Report 44. The comparison was performed in absolute percentage difference between mass attenuation coefficient of sample and soft tissue.

Table 2. Mass attenuation coefficients of paraffin wax and NaCl in energy range between 88 keV and 1.33 MeV. X (%) is an absolute percentage relative difference between experimental and theoretical values of mass attenuation coefficient.

Eγ (keV)	A (%)	B (%)	C (%)	D (%)	E (%)	F (%)	G (%)	H (%)	I (%)
87.83	7.7	7.8	5.91	7.2	7.6	4.17	8.9	5.4	2.7
662.00	1.16	0.73	1.18	3.49	1.18	1.22	1.23	0.38	1.51
834.85	2.53	2.56	1.32	1.33	2.67	2.7	0.28	0.43	1.56
1173.24	4.55	4.62	3.07	4.76	3.13	4.84	1.61	0.32	1.58
1274.53	1.59	1.61	0.53	0.21	0.73	1.67	1.69	0.88	1.39
1332.50	0.69	0.57	1.67	1.69	1.72	5.08	3.51	0.9	1.27

Table 3. Standard deviation, variance and mean of mass attenuation coefficient of all samples.

Sample	A	B	C	D	E	F	G	H	I
Standard Deviation	0.044	0.044	0.046	0.046	0.047	0.049	0.051	0.051	0.053
Variance	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.003	0.003
Mean	0.104	0.104	0.104	0.104	0.104	0.103	0.103	0.102	0.103

Figure 2 shows an absolute percentage difference between mass attenuation coefficients of samples A to F. Sample D is chosen as the best sample to mimic human soft tissue because the mass attenuation coefficient of sample D is close to mass attenuation coefficient of soft tissue.

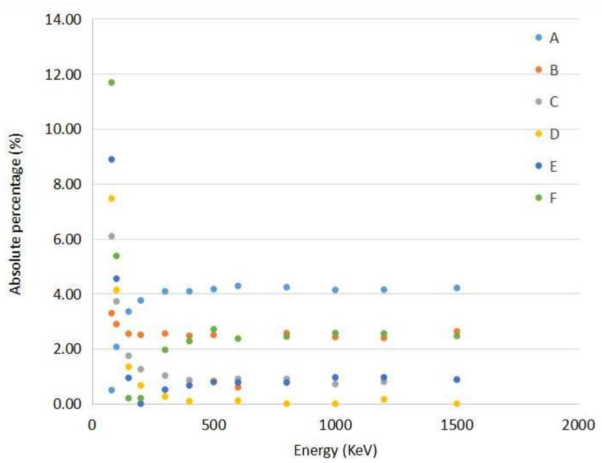

Figure 2. Absolute percentage difference between experimental and theoretical value of mass attenuation coefficients of samples A to F.

Results from Figure 2 shows that composition of paraffin wax without NaCl is unsuitable to represent as soft tissue equivalent material. Table 4 shows the mass attenuation of sample D, soft tissue and the percentage difference between the mass attenuation coefficients of sample D and soft tissue. Table 4 shows that mass attenuation coefficient of sample D has a good agreement with mass attenuation coefficient of soft tissue obtained from ICRU Report 44.

Table 4. The mass attenuation coefficients of sample D and soft tissue.

E_γ (keV)	Sample D	Soft Tissue	Percentage difference (%)
80	0.196	0.182	7.46
100	0.176	0.169	4.13
150	0.151	0.149	1.34
200	0.137	0.136	0.66
300	0.118	0.118	0.26
400	0.105	0.105	0.10
500	0.096	0.096	0.07
600	0.089	0.089	0.06
800	0.078	0.078	0.00
1000	0.070	0.070	0.01
1200	0.063	0.063	0.02
1500	0.057	0.057	0.02

Figure 3 shows absolute percentage difference between experimental mass attenuation coefficients of samples G to I with mass attenuation coefficient of bone based on ICRU Report 44. It shows that sample H has smallest percentage difference as compared to other samples.

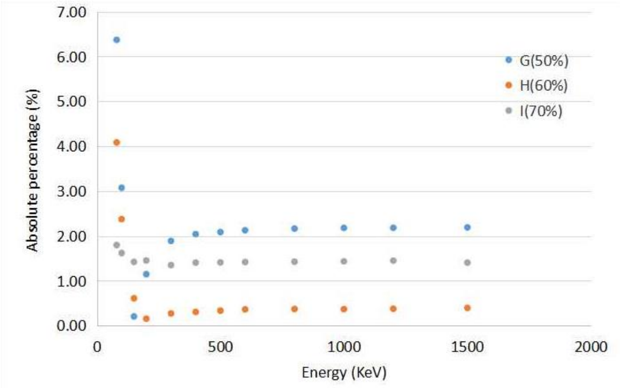

Figure 3. Absolute percentage difference between experimental mass attenuation coefficients of samples G with mass attenuation coefficients of bone.

Table 5 shows the mass attenuation coefficient of sample H, bone and percentage difference between experimental mass attenuation coefficients of sample H and mass attenuation coefficient of bone. Results show that sample H is in good agreement with mass attenuation coefficient of bone obtained from ICRU Report 44.

Table 5. The mass attenuation coefficients of sample H and mass attenuation coefficient of bone.

E_γ (keV)	Sample H	Bone	Percentage diff (%)
80	0.214	0.223	4.08
100	0.181	0.186	2.37
150	0.147	0.148	0.61
200	0.131	0.131	0.15
300	0.112	0.111	0.27
400	0.099	0.099	0.30
500	0.091	0.090	0.33
600	0.084	0.083	0.36
800	0.073	0.073	0.37
1000	0.066	0.066	0.37
1250	0.059	0.059	0.37
1500	0.054	0.053	0.39

Analysis of absolute percentage difference between experimental mass attenuation coefficients of sample D, PMMA and water with mass attenuation coefficients of soft tissue was performed and results were plotted in Figure 4. It shows that the absolute percentage difference between experimental mass attenuation coefficients of sample D and water with mass attenuation coefficient of soft tissue are similar at energy 150 keV. The absolute percentage difference between experimental mass attenuation coefficients of PMMA and mass attenuation coefficients of soft tissue are higher compared to sample D and water at energy 150 keV.

When the energy increases up to 200 keV, the absolute percentage difference between experimental mass attenuation coefficients of sample D and mass attenuation coefficients of bone tissue is smaller compared to absolute percentage difference between experimental mass attenuation coefficients of water and mass attenuation coefficients of PMMA. These results show that mass attenuation coefficients of sample D is closely mimic soft tissue.

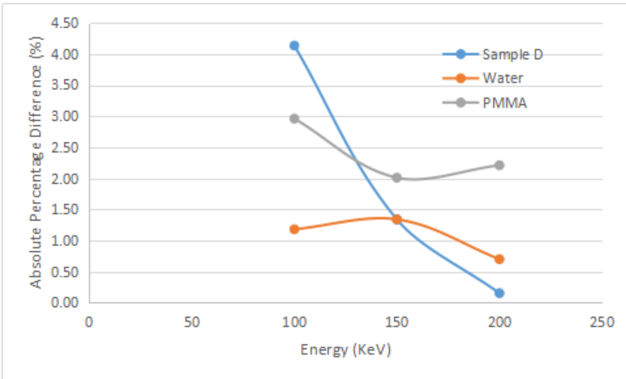

Figure 4. Absolute percentage difference between experimental mass attenuation coefficients of sample D, PMMA and water with mass attenuation coefficients of soft tissue.

Figure 5 shows the absolute percentage difference between mass attenuation coefficients of sample H and teflon with mass attenuation of bone. These results show that mass attenuation coefficient of sample H is closely mimic bone compared to Teflon at energy range of 100 to 200 keV.

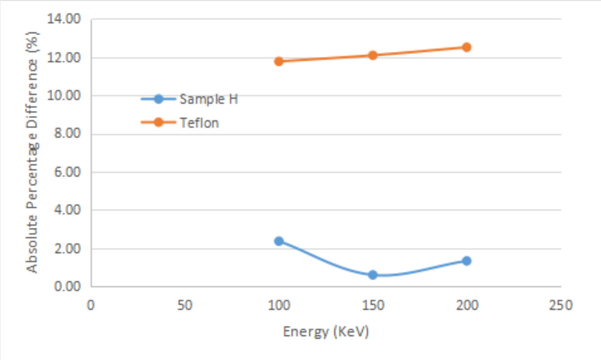

Figure 5. Absolute percentage difference between mass attenuation coefficients of sample H and teflon compared to bone tissue.

IV. CONCLUSION

In conclusion, a combination of 75% of paraffin wax and 25% of NaCl is the best composition to mimic soft-tissue equivalent material, while, a combination of 60% of paraffin wax and 40% of NaCl is suitable for bone equivalent material. In this study, both samples were evaluated successfully within energy range of 87.83 keV and 1332.50 keV.

A good agreement achieved between experimental mass attenuation coefficients of the samples and ICRU Report 44. Both selected samples of tissue equivalent materials are recommended for phantom fabrication to simulate radiation interaction of human body in therapeutic and nuclear medicine.

V. ACKNOWLEDGEMENT

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VI. REFERENCES

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