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An Evaluation of Some Common Laboratory Materials by X-ray Attenuation, for use as Human Tissue Substitutes

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Abstract

To develop readily available laboratory materials for probable use as imaging phantoms or test objects, Laboratory Magnesium Sulphate (MgSO4) and Table salt (NaCl) were used in the ratio 80:20% by weight with paraffin wax to form test materials (MgSO4:PW1) and (NaCl:PW2). Rice powder, gelatine separately, and a combination of gelatine (20g in 100ml of warm water) and 100g rice powder were also made into test objects. The ratios used were confirmed by matching different constituents by weight of the test samples with the web based photon interaction software XCOM designed by the National Institute of Science and Technology, USA, to obtain close matching with tissue data. Each test object was made into 1 cm blocks for exposure to narrow beam x-rays over the diagnostic energy range (50 – 150kV) under automatic exposure conditions. Good agreement within 10%, was found between the measured and calculated values for four of the five tested samples. Matching of the tested materials with mass attenuation coefficients of simulated tissue showed acceptable match at high photon energies of 0.04 – 0,05 MeV and above for gelatine, PW1 (paraffin wax + $MgSO_4.6H_2O$) and *Rigel* (Rice + gelatine). These materials can therefore be used as tissue substitutes in image quality studies.

Introduction

Radiation effects on human tissue are not desirable. As a result research involving frequent ionising irradiation of subjects usually employs tissue substitutes and phantoms.

Over the years many materials have been used as tissue substitutes in medical and radiation physics. Test objects are usually designed for specific tasks [1]. Physical test objects have been used in nodule simulation. Also, nylon beads [2], digitally projected Gaussian nodules on radiographs [3], square lesions [4] models for simulated nodules [5] have all played a part in the development of this subject.

The ICRU Report 44 [6] states that elementally accurate tissue substitutes would have a wider range of applications and be particularly suited to low energy transmission measurements. Such high level of accuracy is still to be achieved. Despite several attempts and the development of a wide range of tissue substitutes as well as new and varied methods of making them, the optimum substitute is yet to be found. This is because no one material possesses all the characteristics of human tissue.

In this study, x-ray attenuation property of some materials was explored in a simple, inexpensive manner to assess their applicability in soft tissue simulation in clinical imaging settings.

Methodology for theoretical calculation of attenuation data

The study was carried out in two parts. First the preparation of the materials in the laboratory with tests against a web based photon interaction data software, and the exposure of the selected materials which matched target tissues, to x-rays to determine attenuation coefficients.

Laboratory Magnesium Sulphate (MgSO4) and Table salt (NaCl) were added in different concentrations to paraffin wax to form the test materials. The ratio of the mixtures as used was in this study was 80:20% (MgSO4:PW1) by weight, to yield MgSO4-PW1 and 80:20% (NaCl:PW2) to give NaCl-PW2, respectively. Also, rice powder, gelatine and a combination of gelatine and rice powder made from dissolving 20g of gelatine in warm water and adding 100g rice powder to make a paste (*Rigel*). Different ratios of constituent elements or compounds in each mixture were used as input data in XCOM, a web-based photon interaction calculation software designed by the National Institute of Science and Technology, USA [7]. The composition by weight and the determined densities are presented in Table 1.

XCOM data was used comparatively to exclude those ratios of material mixtures which had poor matching with soft tissue. The theoretical values of μ/ρ obtained for each mixture composition from the XCOM data was matched with the mass attenuation coefficient of soft and lung tissues in the ICRU[8]. Attenuation data for the materials (mixtures) was determined over the range of energies from 1.00 E-03 to 1.00 E+05 MeV. Comparisons were made at the energy range close to diagnostic radiology (0.02 to 0.08 MeV). These energy values were obtained by the conversion of the tube potential values (50 to 150 kVp) used in this work to their energy equivalents. The ratio of each mixture that most closely matched the tissues being simulated was used for further studies.

Results of theoretical attenuation data calculation

Figure 1 shows graphs matching the theoretical attenuation data of each tested material to those of the tissues in ICRU publication 46 [8](ICRU 1992).

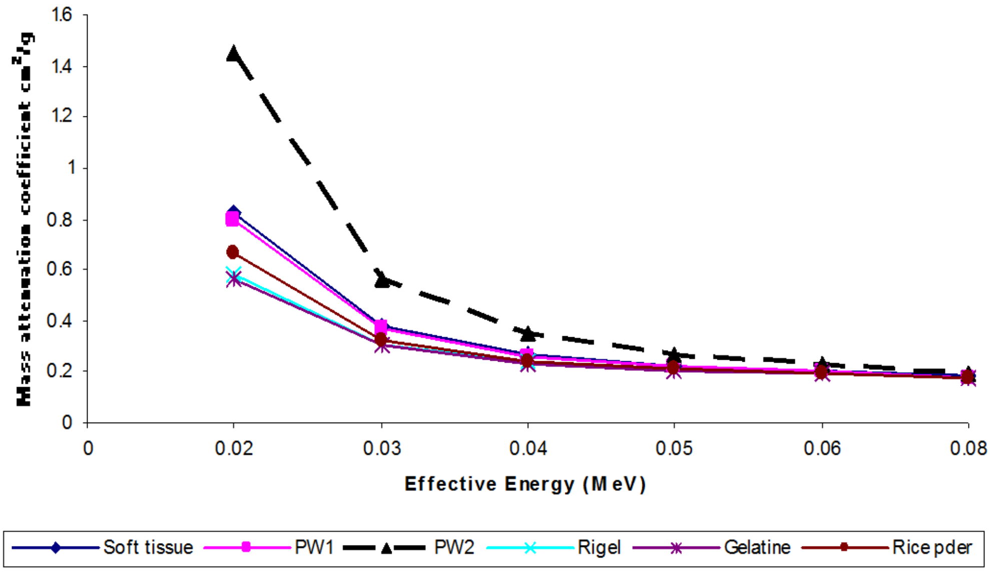

Figure 1: Matching of selected material with μ/ρ of soft tissue

Good matching was indicated by how close the values of mass attenuation were to each other for the compared materials. All the materials showed better match with increasing energy with wide discrepancies occurring at lower energies. The mean percent difference between the values of mass attenuation coefficient in ICRU tissue and those of the tested materials over the range of energies is presented in Figure 2. Material composition with the closest match to the mass attenuation coefficients of lung and soft tissue were adopted for the study. Overall, PW2 showed the poorest quality of match and was therefore dropped. Table 1 shows the % composition by weight of the resulting mixtures.

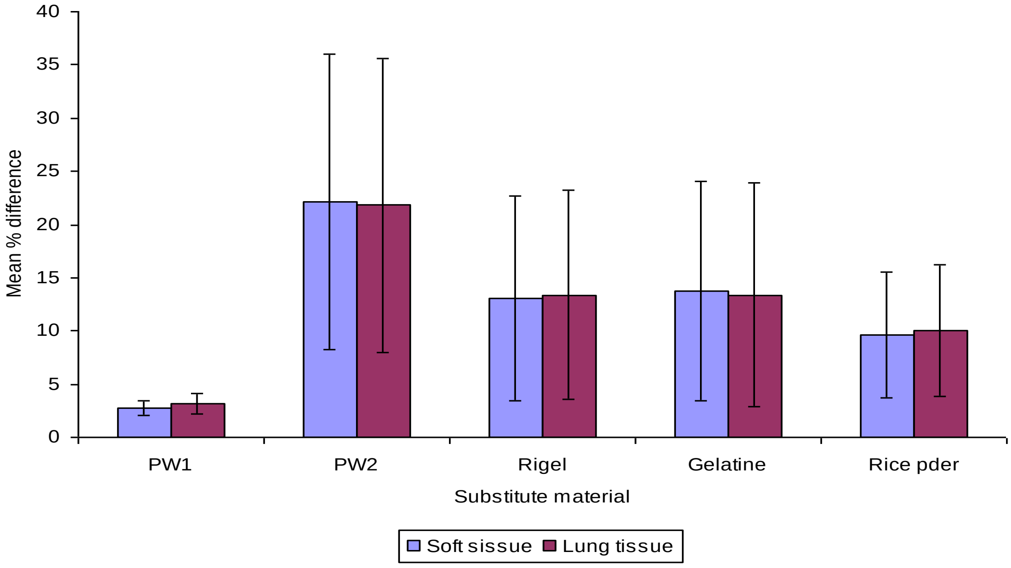

Figure 2: Mean percent differences of µ /ρ values of test materials (XCOM) and ICRU values for tissue over the range of energies.

Table 1: Composition by weight, density (ρ) and electron density (n_o) of tissue substitutes studied.

Materi al	*% Composition by weight of compounds in the mixture	ρ (g/cm^{-3})	n_o (x 10^{28} m^{-3})
PW1	$C_{25}H_{52}$ (50); $MgSO_4.6H_2O$ (50)	0.88	3234
PW2	$C_{22}H_{52}$ (80); NaCl (20)	0.85	3325
Rigel	$C_6H_{12}O_6$ (17); $C_{17}H_{32}N_5O_6$ (83)	1.04	3564
Gelatine	$C_{17}H_{32}N_5O_6$ (100)	0.89	3067
Rice	$C_6H_{12}O_6$ (100)	0.81	2738

* Compositions were arrived at by altering the values in XCOM environment to obtain the photon attenuation properties that most closely represented those of the simulated tissue.
PW – Paraffin wax; *Rigel* – Rice powder in gelatine solution.
ICRU n_o values for (deflated) Lung and (skeletal) muscle = 3480 x 10^{26} m^{-3}

Experimental determination of attenuation properties

The XCOM software uses approximations to carry out theoretical calculations and would therefore not be exact. It is also possible that the theoretical materials are not exactly as specified [9]. For these reasons, and in other to obtain attenuation data for PW1 and *Rigel*, which have not been previously reported, x-ray attenuation experiments were conducted with the samples made into 1 cm thick blocks for this purpose.

The paraffin wax (PW) based samples were prepared by melting the wax and adding the percent weight of respective salts as indicated in Table 1. A paste each, of rice and gelatine samples was made by adding each substance, respectively, to water and allowing it to set within a 1 cm thick mould. *Rigel* was made by mixing rice powder in a solution of gelatine at 35^{o} C. The slight temperature increase was to facilitate proper mixing of the compounds. *Rigel* mixture, gelatine and rice samples were placed in a vacuum cupboard during drying to remove air trapped within the matrix of the mixture. Where necessary, materials were machined to obtain required thicknesses determined with a precision micrometer.

The materials were then exposed to a narrow beam of x-radiation over the range of energies shown in Table 2. Using the mean values of both the incident x-ray intensities (I_o) and the transmitted intensities (I), obtained from three exposures each, the single ratio of I_o/I for the absorber thickness of 1cm was determined for different tube potentials. The resulting linear attenuation coefficients (μ) for the adopted substitutes, PW1, Gelatine, and *Rigel* were calculated from equation 1.

$$\mu = x^{-1} In(I/I_o) \qquad (1)$$

Mass attenuation coefficients (μ/ρ) of the absorbers were obtained by computing the density (ρ) of each material from the mass and volume and determining the quotient of μ/ρ. Volume of absorbers was determined by method of displacement of water. Calculated density values and electron density estimates are shown in Table 1. The number of electrons (n_o) in each material was estimated from the method of Traub et al. [10] with equation 2.

$$n_o = \rho N_A \sum_i \frac{w_i Z_i}{A_i} \qquad (2)$$

where w_i, Z_i and A_i are the fraction by weight, the atomic number and the molecular weight of the *i*th element. N_A is the Avogadro number.

The values of μ/ρ from this process were compared to the values calculated with 'XCOM'. To do this it was necessary to include the energy range used for the x-ray exposures (50 kVp to 150 kVp corresponding to effective energies in the range 0.0195 to 0.0585 MeV) into the XCOM energy data. This allowed comparison of calculated and theoretical data for the exact energy values. Tested materials were then used in computing the degree of match, with the values of μ/ρ for tissues being simulated taken from ICRU Report 46[8] and using equation 3[10].

$$\frac{(\mu/\rho)_{substitute}}{(\mu/\rho)_{tissue}} \qquad (3)$$

All analysis were restricted to the range of energies used in the experimental measurements (0.0195 – 0.0585 MeV).

Results

A comparison of measured and calculated values of μ/p are shown in Table 2. Analysis of the attenuation properties of the five materials with XCOM showed that four of them matched the photon interaction properties of soft and the lung tissues. Direct measurements of x-ray beam attenuation over the diagnostic radiology energy range gave μ/ρ values with mean percent differences of 6.9 (Gelatine), 10.1 (Rice), 8.7 (PW1) and 8.6 (*Rigel*), from the corresponding values calculated with XCOM. The range of differences for all the materials was 0.01 to 29.2%. Results show that the discrepancies between theoretical and experimental values of mass attenuation coefficient for the tested materials are within 10%. The differences may be attributed to the energy related contribution of scattered or secondary radiation to the transmitted beam [11].

The ICRU[6] recommends that the attenuation properties of materials used as tissue substitutes for radiological imaging should not have an average difference greater than 5%. The results from this study show percent differences higher than 5% for two of the four materials. *Rigel* and Gelatine both recorded an average percent difference of 10 and 10.2 respectively when compared with both soft tissue and lung. These higher values may have been due to the method of material preparation. It is possible that impurities from the mixing process, as well as the presence of some air traps in the finished material could have added to the difference observed. PW1 and Rice recorded percent differences of 3.2 and 4.4 % when matched with the lung tissue and 4% when matched with soft tissue, respectively. The performance of these materials at the lower end of the energy scale was poor, with mean differences in the range 3.7 to 29.2% % between them. Differences between substitute materials and the tissues became smaller as the tube energy increased signifying better match at higher photon energies. The implication of this is that scatter properties are a better match than the absorption properties.

Table 2: Comparison of experimental and calculated values of μ/ρ (cm^2/g)

	Measured (μ/ρ)				XCOM (μ/ρ)			
Energy	**Gel**	**Rice**	**PW1**	***Rigel***	**Gel**	**Rice**	**PW1**	***Rigel***
0.020	0.698	0.778	0.894	0.71	0.598	0.70	0.839	0.615
0.023	0.501	0.601	0.799	0.608	0.426	0.484	0.565	0.436
0.027	0.369	0.485	0.601	0.425	0.339	0.374	0.426	0.345
0.032	0.321	0.346	0.411	0.311	0.286	0.307	0.341	0.289
0.035	0.289	0.311	0.302	0.286	0.259	0.274	0.299	0.261
0.039	0.245	0.285	0.295	0.263	0.239	0.249	0.268	0.24
0.040	0.241	0.266	0.271	0.244	0.235	0.245	0.263	0.237
0.043	0.236	0.253	0.253	0.231	0.224	0.232	0.246	0.231
0.047	0.22	0.231	0.233	0.221	0.214	0.219	0.23	0.221
0.051	0.206	0.209	0.222	0.211	0.206	0.209	0.219	0.206
0.055	0.211	0.211	0.215	0.206	0.199	0.202	0.209	0.200
0.059	0.199	0.202	0.206	0.205	0.194	0.194	0.202	0.194

Gel – gelatine
PW1- paraffin wax + $MgSO_4.6H_2O$

Matching of the tested materials to muscle and lung tissue is shown in Figure 3 for the four materials. The values plotted were derived from equation 3, using data from ICRU [8]. It was observed that the ratio of mass attenuation coefficients of tissue substitute to the tissue increased with the tube energy. The best quality match was found between 0.04 MeV and 0.05 MeV, corresponding to tube potentials between 102 and 150 (kVp) for all the materials. At these energies, the ratio of mass attenuation coefficient of substitute materials to tissue tended towards unity. However at lower energies, the ratio of attenuation coefficients of substitute to tissue was either above or below the expected value.

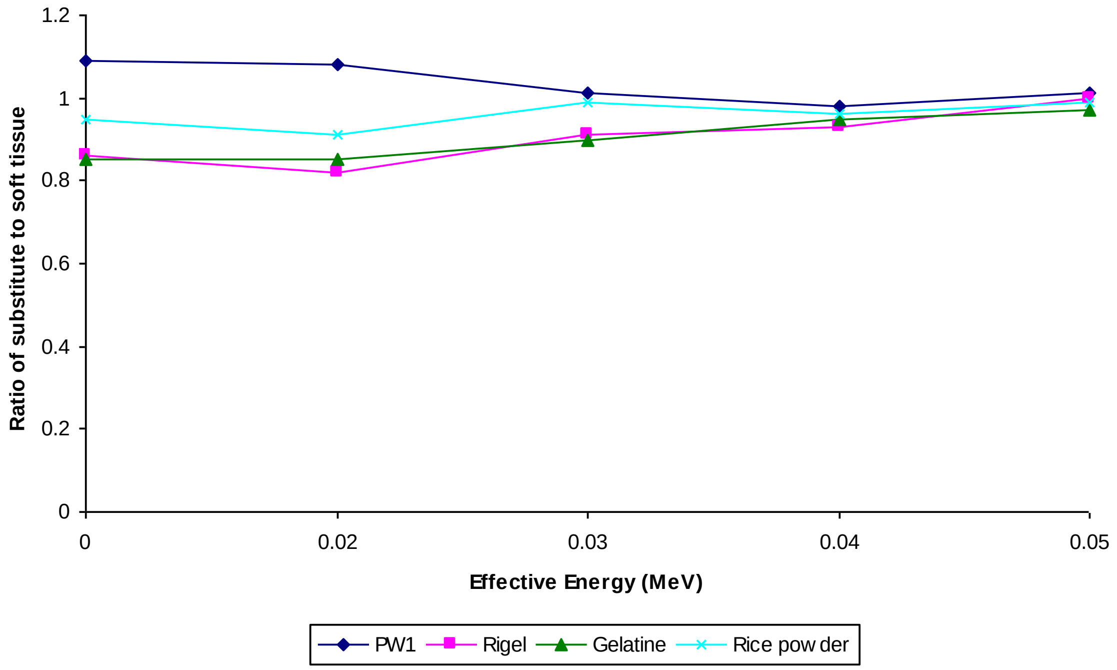

Figure: Ratio of mass attenuation coefficient of test materials with soft tissue. Ratios were determined for energy values reported in ICRU [8].

Discussion

The requirement of sophisticated processing technology for modern polymers restricts medical physics laboratories to basically three types of materials which can be easily manipulated for the purposes of tissue simulation [12]. Wax based, epoxy or resin based and foams (polyurethane) have formed the bulk of efforts at laboratory simulation of tissue. Whatever the material used, the basic criterion of attenuation properties are essential for adoption of a particular substitute. The wide variability encountered in patients and in different pathological states within the same patient makes accurate simulation difficult. This is without prejudice to the fact that no one tissue exactly matches the elemental composition as well as the chemical bonding found in human tissue and no one phantom can be used for all examinations [13].

The linear attenuation coefficient (μ) is proportional to density of the absorber. For this reason, the quotient of μ and ρ (cm^2/gram) is preferred for tabulation as it is independent of the state of the material. Soft tissue substitutes have been severally formulated and paraffin wax, rice and gelatine have been separately mentioned in tissue simulation at some time or the other. Gelatine, a denatured protein has been cited as a tissue substitute for the lungs[12]. Similarly, rice powder has also been used to simulate muscle. Paraffin wax has been reportedly used alone and in combination with some other materials in simulating lung pathologies. The combination of paraffin wax with MgO has been reported to yield a good tissue substitute [14], but $MgSO_4 . 6H_2O$ in paraffin wax has not been previously reported.

According to White [14], 24.7% by weight of MgO in paraffin wax yielded a substitute with maximum discrepancy in μ/ρ of 4%, for about the same energy range as was used in this study. PW1 in the current work yielded a maximum discrepancy below the recommended 5% over the range of energies studied. The performance of this mixture suggests the possibility of its use as a tissue substitute particularly at the energies between 80 keV and 150 keV where there is near perfect match with soft tissue.

The combination of rice and gelatine (*Rige*l) satisfied the intended purpose of the mixture - improved performance relative to photon interaction properties of soft tissue. *Rigel, which is by this study,* a new entrant into tissue simulation, and gelatine both exceeded the recommended criteria with mean discrepancies greater than 5% of the simulated tissues. There is the possibility of achieving lower values by better production methods to ensure there are no impurities and air traps within the material. Some air pockets were observed within the blocks of gelatine and *rigel*, and could have contributed to the higher discrepancies observed.

The electron densities (n_o) of these materials (Table 1) are two orders of magnitude higher than the values reported in ICRU 44 for muscle and lung (deflated). Differences are expected because the materials used cannot be said to be in their purest state. Besides, the elemental compositions of soft tissue includes trace elements [15] most of which are not found in the tested mixtures. It would be interesting to examine the effects these trace elements would have on these materials at the tested and lower energy ranges. No attempt was made in the current study to assess the performance of these materials at energies lower than 0.02 MeV because that was beyond the scope of this work. It was intended to obtain materials that would be useful in lesion simulation for image quality assessment. From the results, any of PW1, gelatine and *rige*l could be used for the intended purpose in the current study, particularly at higher energies.

Maughan and colleagues [16] have shown variations in the composition of diseased tissue from normal tissue, and even variation of normal tissue as a result of age and dietary influences[17]. The substitutes in this work are derived from comparisons with normal tissue. Considering the insufficiency of data related to photon interaction properties of tumours and diseased tissue, the results can be acceptable for simulation, barring any shortfall in terms of image display.

Conclusion

Theoretical studies of five materials were carried out to obtain photon attenuation data at different compositions by weight using the web based photon data calculation software, XCOM. The data was compared to values of soft tissue reported in literature. Compositions that most closely matched expected results were used in experimental x-ray attenuation studies at diagnostic radiology energy range. Four out of five initially selected materials met the conditions for acceptance and were then studied by comparison of their experimentally obtained mass attenuation coefficients with calculated values from XCOM. Good agreement within 10% was found between the measured and calculated values. Matching of the tested materials with mass attenuation coefficients of simulated tissue showed acceptable match at high photon energies of 0.04 – 0,05 MeV and above for gelatine, PW1 (paraffin wax + $MgSO_4.6H_2O$) and *Rigel* (Rice + gelatine). These materials can therefore be used as tissue substitutes. In the current work, one of them (gelatine) was used to simulate subtle soft tissue lesions during image quality studies.

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