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Study of Effective Atomic Number of Muscle Tissue Equivalent Material Using Back-scattering of Gamma Ray Photons

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ABSTRACT

Effective atomic number (Z_{eff}) of muscle tissue equivalent materials are evaluated by using, multiple backscattering of gamma photons. For the verification of tissue equivalent material used as a realistic tissue, measurement of mass attenuation coefficient (μ_m/ρ) and mass absorption energy coefficient (μ_{en}/ρ) are the important parameters. The present work is based on non-destructive technique by using 3" x 3" NaI(Tl) scintillation detector in order to study the effect of target thickness on the intensity distribution of gamma photons. The intensity of multiply back-scattered photons increases with increase in target thickness and gets saturated at a particular depth. This saturation depth of multiply back-scattered photons is used to assign a number (Z_{eff}) to a composite tissue equivalent material. Response function of 3" x 3" NaI(Tl) scintillation detector is applied on the recorded pulse-height distribution to make the experimental results more precise and accurate. Monte Carlo simulation of the tissue equivalent material also supports the present work

Keywords: Effective atomic number, Mass attenuation coefficient, Mass absorption energy coefficient, Saturation depth, Response function.

1. INTRODUCTION

The interaction process taking place inside an exposed tissue depends upon the type of radiation (charged or uncharged), its energy and the elemental composition of tissue. In medical applications such as radiology, nuclear medicine and radiation therapy various dosimetric materials are used as muscle equivalent phantoms. Investigation of muscle equivalency of a material for gamma photon beam is carried out by calculating its effective atomic number (Z_{eff}), mass attenuation coefficient (μ_m/ρ) and mass energy absorption coefficient (μ_{en}/ρ). These various materials are used as phantoms [1]. In intermediate energy range, Compton scattering process dominates and shows its dependency with electron density of the material. Several workers used different materials and have shown the identical radiation characterization effect as of a realistic tissue. Kienbock [2], did work on simulation of water or muscle tissue by taking aluminium foil of thickness 1 mm which absorbs the amount of radiation, equivalent with 10mm thick water or muscle layer. Goodman [3], introduces a liquid with constituents of water (65.60%), glycerol (26.80%) and urea (7.60%) in a finite proportion which is equivalent to a muscle tissue. Harris [4], prepares a tissue equivalent material by mixing paraffin wax with silicon dioxide in definite proportion, and observes the same attenuation properties as a realistic muscle tissue.

The aim of this report is to investigate the muscle tissue equivalence of materials by evaluation of various radiation characterization parameters such as Z_{eff}, μ_m/ρ and μ_{en}/ρ. A non-destructive multiple back-scattering technique (MBST) is used to determine the effective atomic number of the muscle substitute using gamma photons of 662 keV (^{137}Cs). Response function of 3" x 3" NaI(Tl) scintillation detector is applied on the recorded pulse-height distribution to make the experimental results to be precise and accurate. Monte Carlo simulation of the tissue equivalent material also supports the present work.

2. Materials and Methods:

2.1 Muscle substitute:

The muscle equivalent materials which are presented in this work includes water, Goodman liquid and Harris wax.

2.2 Method of Computation:

2.2.1 Total mass attenuation coefficient (μ_m/ρ) and mass energy absorption coefficient (μ_{en}/ρ) calculations

For photons, μ_m/ρ and μ_{en}/ρ data have been calculated for all the tissue substitute and tissue being simulated using mixture rule and the elemental cross-section values generated from WinXCOM [5], by using the relation

$$\frac{\mu_m}{\rho} = \sum_i \omega_i \left(\frac{\mu_\iota}{\rho}\right)_i \quad (1)$$

Where ω_i is weight fraction and $(\mu_l/\rho)_i$ is mass attenuation coefficient of ith element of the chosen tissue equivalent material. The total mass energy absorption coefficient (μ_{en}/ρ) is determined by using the relation,

$$\frac{\mu_{en}}{\rho} = \frac{\sigma_{m,en} N_A}{M} \quad (2)$$

where $\sigma_{m,en}$ is the total molecular absorption cross-section, N_A is Avogadro number and M is the molar weight of tissue equivalent material.

2.3 Experimental Methods:

2.3.1 Effective Atomic Number (Z_{eff}) By MBST:

In this experiment, 3″x 3″ NaI(Tl) scintillation detector detects the gamma radiation coming from the 662 keV source of ^{137}Cs, and resulting pulse-height distribution is recorded on a PC-based MCA which is a standard data acquisition and control package. Detail knowledge of experimental set- up and method of measurements are explained in our previous work [6]. In this report, two types of set of targets are used, in the first set mono-element targets (range $6 \leq Z \leq 50$) could serves for calibration purpose, in terms of multiply back-scattered events, in order to determine the Z_{eff} of the second set of the targets i.e. muscle substitute.

When gamma photon beam of energy 662 keV interacts with tissue substitute under investigation and these interacted gamma photons are detected by the detector placed at 180° with the incoming beam. In order to find out the contribution of back-scattered gamma photons, record the pulse-height distribution with sample and without sample for each thickness for the same time as shown in fig- 1(a). Then subtract the recorded pulse-height distribution with and without sample, and resulting events are the true back-scattered events and these recorded events are registered under backscattering peak in the lower energy range [Fig-1(b), curve-a]. Response function of 3″x 3″ NaI(Tl) scintillation detector when applied on the back-scattered peak, extracts the partially absorbed photons of lower energy range which are actually part of back-scattered peak and add them into it [fig-1(b), curve-b]. Response function application serves as correction to the back-scattering peak and boosts the counts under back-scattered peak as shown in fig- 2(b), resulting an increase in quantity of photons and hence quality of data.

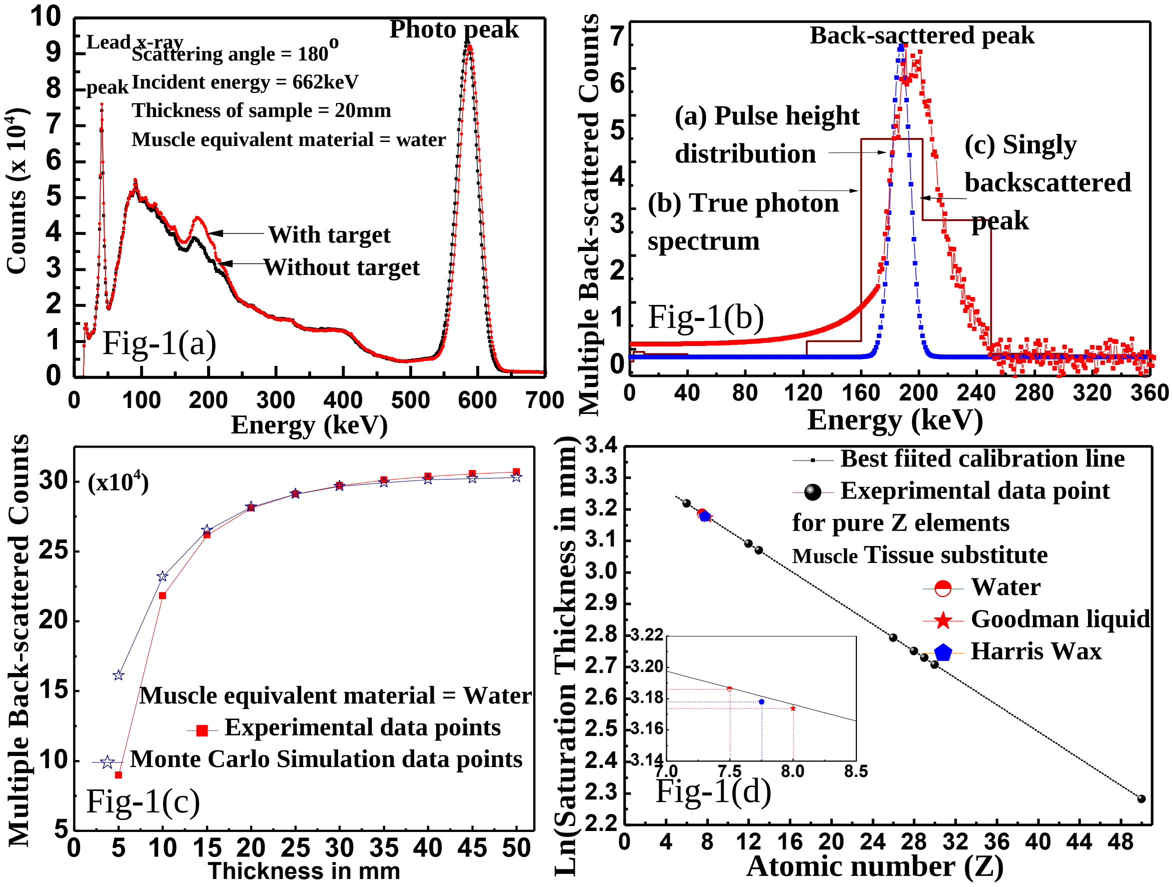

Figure 1: (a) Recorded pulse-height distribution with and without water target for time duration of 15ks, (b) Experimentally observed pulse height distribution, (curve-a) obtained after subtracting background events (unrelated to target). Normalized analytically reconstructed singly scattered full energy peak (curve-c) and resulting calculated histogram (curve-b) of N(E) converting pulse-height distribution to a photon spectrum, (c) comparison of Experimental result with Monte Carlo simulation for water, (d) observed variation of natural logarithm with atomic number

3. Results and Discussions:

In the multiple back-scattering experiment, fig-1(a) shows the recorded pulse height distribution with and without the tissue equivalent material at 662 keV. Without tissue equivalent material spectrum is taken as background (noise). These two pulse height distribution i.e. with and without tissue equivalent material are subtracted to extract the back-scattered gamma photons (back-scattered counts) with tissue substitute only as shown in fig-1(b). We observe that on increasing the thickness of tissue equivalent material, the intensity of back-scattered counts under the back-scattered peak are increases. But at a particular thickness, the multiply back-scattered gamma photons are getting saturated [solid square data points of fig-1(c)] and the values of saturation depth have good agreement with the Monte Carlo simulation calculation (solid star data points). This saturation thickness is used to assign a number to the tissue equivalent material which is named as effective atomic number of that tissue equivalent material. To start with, one has to experimentally calculate the value of saturation thickness for pure element ranging from $6 \leq Z \leq 50$. The value of saturation thickness of pure element serves as reference line for the calculation of effective atomic number of tissue equivalent material as shown in fig-1(d). In table-1, the value of saturation depth are mentioned in column 3rd, the experimentally calculated value of effective atomic number are mentioned in column 4th which have good agreement with the theoretical value of effective atomic number calculated by the empirical formula given by Murty [7].

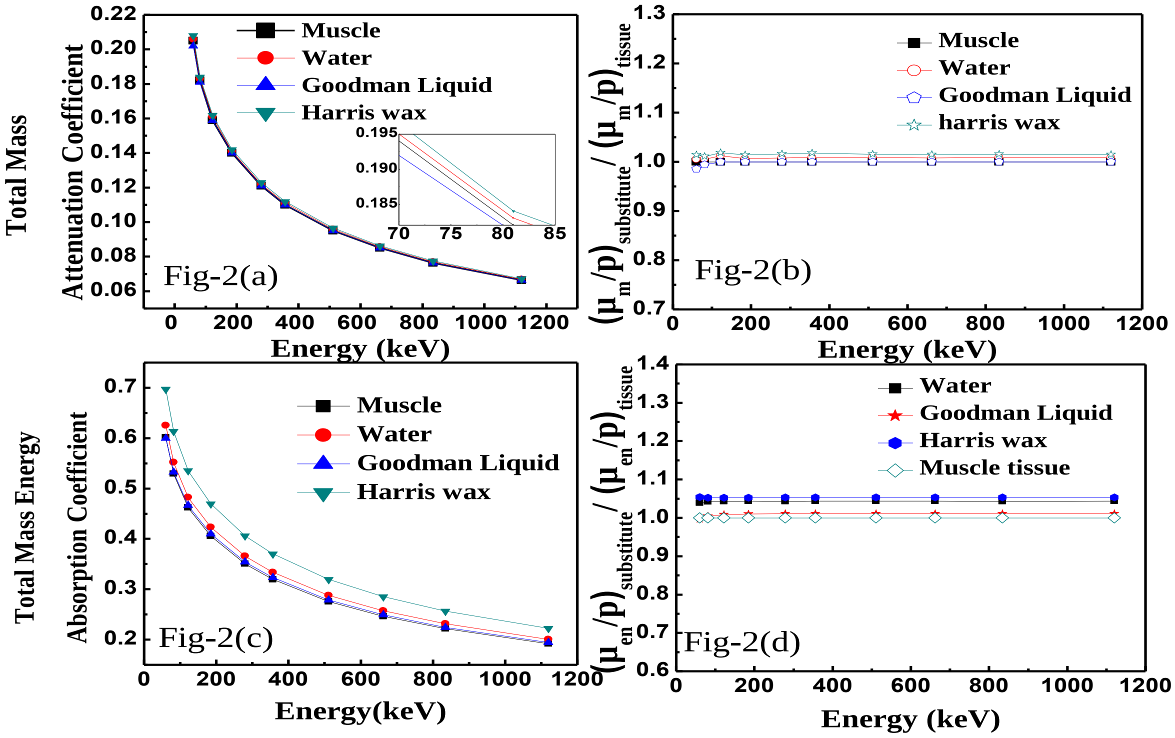

Figure 2:(a) Calculated values of total mass attenuation coefficient for tissue and their equivalent material in the energy range from 60 keV to 1120 keV, (b) Ratios between calculated mass attenuation coefficient for tissue equivalent material and the corresponding calculated values for muscle tissue, (c) Calculated values of total mass energy absorption coefficient for tissue and their equivalent material in the energy range from 60 keV to 1120 keV, (d) Ratios between calculated mass energy absorption coefficient for tissue equivalent material and the corresponding calculated values for muscle tissue.

Table 1- Experimentally determined values of saturation depth and Z_{eff} for tissue equivalent material

Substitute or Tissue	**Energy (keV)**	**Saturation Depth(mm) (Experimentally)**	**Z_{eff} (Experimentally)**	**Z_{eff} (Theoretically) [7]**
Muscle	-	-	-	7.71
Water	662	24.2	7.50 ± 2.34%	7.68
Goodman Liquid	662	23.9	8.00 ± 7.09%	7.47
Harris Wax	662	24.0	7.75 ± 2.10%	7.59

Fig-2(a) shows the mass attenuation coefficient (μ_m/ρ) for muscle, water, Goodman liquid and Harris wax as the function of gamma photon energy range 60 keV to 1120 keV. The values of μ_m/ρ for water, Goodman liquid and Harris wax are nearly equal with the value of $(\mu_m/\rho)_{tissue}$ of the muscle and same results are obtained for the total mass energy absorption coefficient (μ_{en}/ρ) which are shown in fig-2(c). The ratios of mass attenuation coefficient (μ_m/ρ) and mass energy absorption coefficient (μ_{en}/ρ) between the muscle and their substitute are shown in fig-2(b) and 2(d). On comparing the entire three equivalents material to muscle tissue, then concluded that the value of Goodman liquid have in the best agreement with the value of muscle tissue other than Water and Harris wax. Hence the computed values are useful in the simulation of tissue substitute [1, 5, 8-9].

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