A NEW METHOD FOR CORRECTION OF ABSORTION OF RADIATION IN BIOLOGICAL SAMPLES USING RAYLEIGH TO COMPTON SCATTERING RATIO

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Abstract. *The aim of this work is to develop a method for correction of absorption of radiation (the mass attenuation coefficient curves) to using the Rayleigh to Compton scattering ratio produced by a gamma-ray source of Am-241(59.54 keV) in biological samples (prostate tissues, milk powder, V-10 and NIST 1557B bovine liver). The prostate tissues used in this study were provided by the Laboratory of Cell Interactions in the Endocrine and Reproductive systems of the Department of Histology and Embryology of the ICB/CCS/UFRJ. The experimental measurements were obtained using the system EDXRF of the Nuclear Instrumentation Laboratory (LIN-COPPE/UFRJ) with a source Am-241. Rayleigh to Compton scattering measures were also taken from NIST 1577B certified samples of bovine liver for experimental validation of measures. The results obtained by the propose method were compared with the transmission method.*

Keywords*: prostate tissues, mass attenuation coefficient, Rayleigh scattering, Compton scattering.*

1. INTRODUCTION

The attenuation of X-rays by material provides a wide variety of information about fundamental properties of matter in the atomic, molecular, and solid state In particular, relative and absolute measurements of the mass attenuation coefficients are very important in energy disperse X-ray fluorescence technique (EDXRF). Besides that, in the case of biologic samples the determination of the X-ray mass attenuation coefficients is an essential parameter for quantitative analysis, because of its basic composition is formed by H, C, Mg, Na, S, Cl, P, K and Ca. In the literature we found some methods to correction of the coefficient of X-ray absorption EDXRF. The method of transmission of radiation (Leroux and Mahmud, 1966) estimates the absorption factor of the sample making measures of the intensity of characteristic X-rays, emitted by a multi target, placed adjacent to the sample. The method of transmission-emission (Anjos, 2000) is a variant of the method of transmission. This method is based on the assumption that the absorption coefficient of radiation in the sample can be represented by a power of energy E of the radiation incident. Our work proposes the development of a new method for determination of mass attenuation in samples with low atomic number based on Rayleigh to Compton scattering ratio and the effective atomic number.

2. THEORICAL CONSIDERATIONS

In interaction of photons with low-energy electrons very connected, the interaction can occur where the atom absorbs all the backtracking and practically no photon loses energy, simply changing its direction. This kind of interaction is called scattering Rayleigh or incoherent, and the direction of scattering is predominant forward (Cesareo *et al*, 1992). The scattering of electrons bound to atoms is done fixing up the Thomson cross section for the electron free, considering the possibility of interference of scattered radiation. This correction appears as a Fourier transform of the density of charge, known as form factor (Kahane, 2001).

$$\left(\frac{d\sigma}{d\Omega}\right)_R = \left(\frac{d\sigma}{d\Omega}\right)_{Th} . [F(x,Z)]^2 \tag{1}$$

where Z is the atomic number and x is the momentum transfer.

Unlike Rayleigh scattering, the Compton scattering, or incoherent, occurs from the interaction between a photon and a free electron. In this process the photon is completely absorbed. The result of this interaction is the emergence of another photon being on the direction θ of the original photon scattered in a direction. The photon transferred energy and momentum for the electron (Anjos, 1991). The Compton cross section is evaluated from:

$$\left(\frac{d\sigma}{d\Omega}\right)_C = \left(\frac{d\sigma}{d\Omega}\right)_{KN} . [S(x,Z)] \tag{2}$$

where Klein-Nishina refers to Compton cross section for a free electron at rest, while the incoherent scattering function *S(x,Z)* corrects for the fact that actually the electron is bound in an atom and moving.

The scattering Rayleigh and Compton are functions of the parameters of correction factor in *F(x,Z)* and the scattering function *S(x,Z)*, which depends on the momentum transfers and the atomic number. Thus, for given momentum transfers, the function S and F depend only of the atomic number. Obtaining the ratio of the cross section, we have:

$$\frac{\left(\frac{d\sigma}{d\Omega}\right)_R}{\left(\frac{d\sigma}{d\Omega}\right)_C} = \left\{\frac{\left(\frac{d\sigma}{d\Omega}\right)_{Th}}{\left(\frac{d\sigma}{d\Omega}\right)_{KN}}\right\} . \frac{[F(x,Z)]^2}{[S(x,Z)]} \tag{3}$$

In the case of a solution containing n different elements, we can generalize the equation adding up to factor in *F(x,Z)* and incoherent scattering function *S(x,Z)* the percentage of each atomic element.

$$\frac{\left(\frac{d\sigma}{d\Omega}\right)_R}{\left(\frac{d\sigma}{d\Omega}\right)_C} = \left\{\frac{\left(\frac{d\sigma}{d\Omega}\right)_{Th}}{\left(\frac{d\sigma}{d\Omega}\right)_{K-N}}\right\} . \frac{\sum \alpha_i^{at}.[F(x,Z_i)]^2}{\sum \alpha_i^{at}.S(x,Z_i)} \tag{4}$$

where:

$$\alpha_i^{at} = \frac{\left({}^{w_i}/_{A_i}\right)}{\Sigma\left({}^{w_i}/_{A_i}\right)} \tag{5}$$

α_i^{at} is the percentage of mass and w_i is the atomic number of each element A_i.

For a mixture, the ratio cross sections depends only effective atomic number Z_{eff}, which is a complicated function of atomic number present in each compound. Therefore, knowing it the Rayleigh to Compton scattering ratio, we can get the curve of radiation absorption for a specific type of sample.

3. MATERIAL AND METHODS

3.1. Attenuation Coefficient

A beam of gamma radiation when focused on a material of thickness *D*, a fraction of the beam is absorbed by the material. The intensity of the beam that emerges is linked to the intensity I_0 of the incident beam, the Beer-Lambert law, being valid for a monoenergetic beam of radiation (Knoll, 1980):

$$I = I_0 . e^{-\mu D} \tag{6}$$

where μ is called the linear attenuation coefficient. The linear attenuation coefficient is the probability of suffering beam attenuation to the processes of photoelectric absorption, Compton scattering or pair production and can be written as:

$$\mu = \tau(photoeletric) + \sigma(Compton) + \kappa(pair\ production) \tag{7}$$

The linear attenuation coefficient is limited by the fact that it varies with the density of the absorber, even though the absorber material is the same. Therefore, the mass attenuation coefficient is much more widely used and is defined as:

$$\mu_m = \mu/\rho \tag{8}$$

where ρ represents the density of the medium. For a given gamma-ray energy, the mass attenuation coefficient does not change with the physic state of a given absorber.

$$I = I_0.e^{-\mu_m.\rho.D} \tag{9}$$

The method of transmission used this work consist in determine experimentally of the mass attenuation coefficient through of the Beer-Lambert law:

$$\mu_m = \left(\frac{1}{\rho D}\right).\ln\left(\frac{I}{I_0}\right) \tag{10}$$

3.2. The methods of determination effective atomic number

Five methods to determine the effective atomic number by Rayleigh to Compton scattering ratio in the literature were used in calculating the absorption coefficient. Below the description of each of the five methods:

3.2.1. Method I

In the first method, Harding (1995) assumed that the ratio between Rayleigh to Compton scattering ratio is a function power of effective atomic number:

$$R = K.\left(Z_{eff}\right)^A \tag{11}$$

where K represents the Thomson to Klein-Nishina cross section ratio and A is a power of Z_{eff}. We can assume that the Rayleigh and Compton scattering are proportional to Z^3 and Z, respectively (Manninen, 1984). Thus, we get the following definition of Z_{eff}.

$$\mathbf{Z_{eff}} = \left[\frac{\Sigma\left(\mathbf{w_i}/\mathbf{A_i}\right).\mathbf{Z_i^3}}{\left(\mathbf{w_i}/\mathbf{A_i}\right).\mathbf{Z_i}}\right]^{\mathbf{1}/\mathbf{2}} \tag{12}$$

3.2.2. Method II

The method propose for Duvauchelle *et al.* (1999) use the atomic form factor $F(x,Z)$ and the incoherent scattering function $S(x,Z)$, as depends of the atomic number and of the momentum transfer x. For each value of the momentum transfers, there is a discrete function f_x that provides the value of Z as a function of F^2/S.

$$Z = f_x^D\left(F^2/S\right) \tag{13}$$

For a sample formed by a composite of several elements, we can consider that the functions f_x are continuous and allow us calculate the value of Z_{eff} .

$$Z_{eff} = f_x\left[\frac{\sum\alpha_i^{at}.[F(x,Z_i)]^2}{\sum\alpha_i^{at}.S(x,Z_i)}\right] \tag{14}$$

$$Z_{eff} = f_x\left[\left(F^2/S\right)_{eff}\right] \tag{15}$$

We can deduce the equation f_x through a set of appropriate curve. That way you can determine the value of Z_{eff} know the value of $(F^2/S)_{eff}$ of the sample considered.

3.2.3. Method III

Tsaï and Cho(1976) suggest an empirical formula, very similar to the previous one, making use of the electronic percentage A. According to the authors, this expression is valid for energies below 150 keV.

$$Z_{eff} = \left[\sum_i \alpha_i^e . Z_i^{3.4}\right]^{1/3.4} \tag{16}$$

with

$$\alpha_i^e = \frac{\left({w_i}/{A_i}\right).Z_i}{\sum\left({w_i}/{A_i}\right).Z_i} \tag{17}$$

3.2.4. Method IV

According Puumalainen (1977) the effective atomic number is the mean number of electrons per atom. Using the atomic percentage α_i^{at}, we can write equation below:

$$Z_{eff} = \sum_i \alpha_i^{at} . Z_i \tag{18}$$

3.2.5. Method V

This method, we obtained the effective atomic number using the empirical relation (Singh, 2007) given below:

$$Z_{eff} = \{\sum_i f_i . (Z_i)^{2.94}\}^{(1/2.94)} \tag{19}$$

where f_i is fraction of total number o electrons associated with each element and Z_i is atomic number of each element.

4. EXPERIMENTAL

The experimental set-up was composed by: Am-241 gamma source, an AMPTEK CdTe detector, with an energy resolution of about 530 eV at 14.4 keV and an ORTEC multichannel-analyser. The experiment was performed on various materials of different effective atomic number, $6 \leq Z \leq 16$, for 59.54 keV incident photons. The support system that sets the sample, allows to set-up a source of Am-241 range, thus maintaining all fixed geometry of detection. The angle between the emerging beam that reaches the detector and the surface of the sample is approximately 90 ° and the incident angle was 16°, which creates an angle of scattering of 106°. Samples were prepared in pellet form with superficial density of about 400 mg/cm². The samples used were: H_3BO_3, Na_2CO_3, $CaCO_3$, Al_2O_3, Na_2CO_3 and MgO. Each sample measured in a time of 5000 s. The figure 1 shows the picture of the experimental set-up.

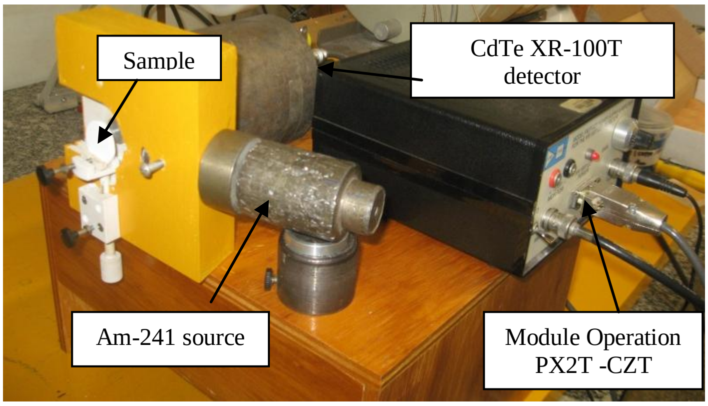

Figure 1.Picture of the experimental set-up.

The figure 2 shows gamma ray scattering spectrum for Americium source in a time of 5000 s.

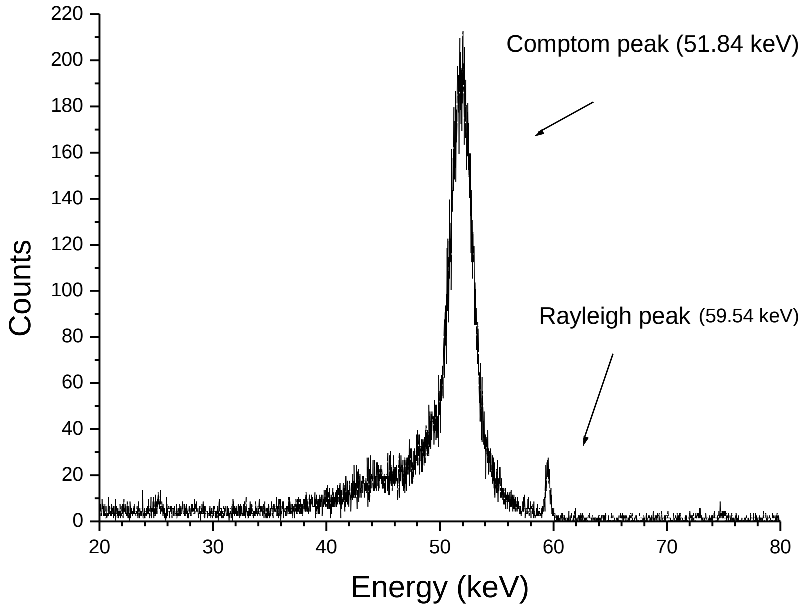

Figure 2.Picture of the experimental set-up.

In order to apply the method of transmission, the experimental set-up was composed by: Am-241 gamma source non-sealed, an ORTEC Si(Li) detector, with an energy resolution of about 180 eV at 5.9 keV and an ORTEC multichannel-analyser. This configuration, the Si(Li) detector, the sample and Am-241 source non-sealed are aligned so that transmission occurs only in gamma-ray. Each sample measured in a time of 300 s. The method of transmission was applied for the energies of 13.95 keV, 17.74 keV, 22.12 keV, 26.36 keV and 59.54 keV of the Am-241 source non-sealed. The figure 3 shows the picture of the experimental set-up used method of transmission.

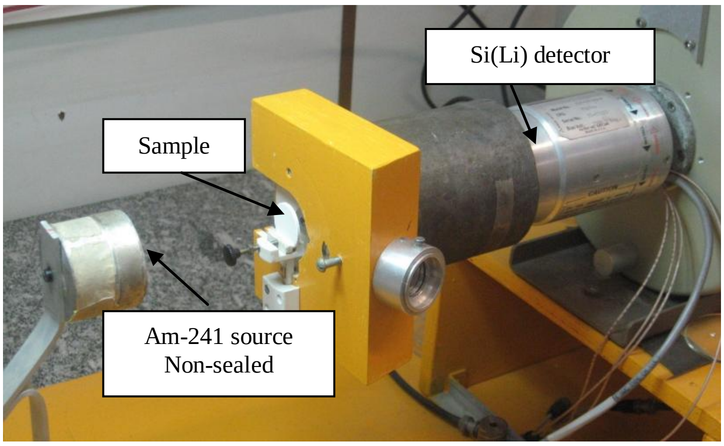

Figure 3.Picture of the experimental set-up of the method of transmission.

The figure 4 shows spectrum of the Am-241 source non-sealed.

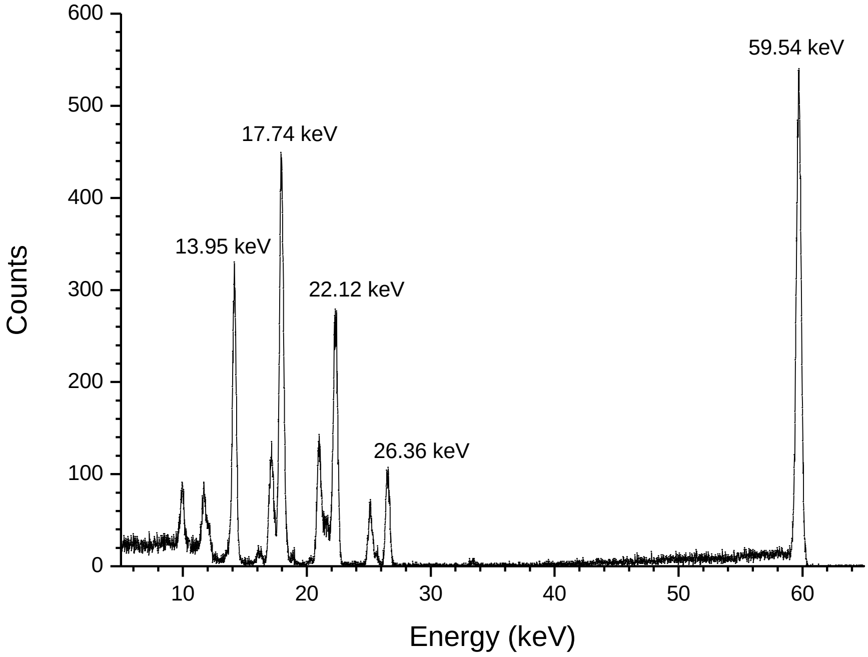

Figure 4.Spectrum Am-241 source non-sealed.

5. RESULT

Applying both methods for samples of H_3BO_3, Na_2CO_3, $CaCO_3$, Al_2O_3, K_2SO_4 Na_2CO_3 and MgO, we found the values of Z_{eff} of each sample and determine the Rayleigh to Compton ratio. The tables 1 the results:

Table 1.Result of Rayleigh to Compton peaks scattering ratio for Am-241 source (59.54 keV) and effective atomic number (Z_{eff}) found for each method.

Sample	Rayleigh/ Compton	Zeff Method I	Zeff Method II	Zeff Method III	Zeff Method IV	Zeff Method V
H_3BO_3	0,0023	6,9	7,7	7,3	7,1	7,4
Na_2CO_3	0,0061	9,2	9,5	9,4	9,1	9,4
MgO	0,0114	10,6	10,8	10,8	10,4	10,7
Al_2O_3	0,0123	10,8	11,1	11,2	10,6	11,1
$CaCO_3$	0,0188	14,0	13,0	15,5	12,6	15,1
K_2SO_4	0,0217	15,1	14,3	16,0	14,4	15,8

Plotting a curve of the Rayleigh to Compton ratio in each sample by effective atomic number, we can find the effective atomic number of a sample unknown element composition. The table below shows the values of three certified samples and prostate tissues found from this curve for each method applied.

Table 2.Result of Rayleigh to Compton scattering ratio for samples of Prostate Tissues, Bovine Liver, Milk Powder and V-10 and yours effective atomic number (Z_{eff}) found for each method.

Sample	Rayleigh/ Compton	Zeff Method I	Zeff Method II	Zeff Method III	Zeff Method IV	Zeff Method V
Prostate Tissues	0,0033	7,5	8,3	7,6	7,7	7,7
Bovine Liver	0,0027	7,2	7,9	7,4	7,4	7,4
Milk Powder	0,0035	7,6	8,4	7,7	7,9	7,8
V-10	0,0055	8,4	9,2	8,7	8,8	8,7

The objective of these measures was to find the mass attenuation coefficient of the samples through the scattering produce by sample, and compare with the simulated values in XCOM. The values found mass attenuation coefficients for five methods were the values founds for method of transmission. The figures 5, 6, 7 and 8 shows the results found for each sample on the each energy of the source non-sealed.

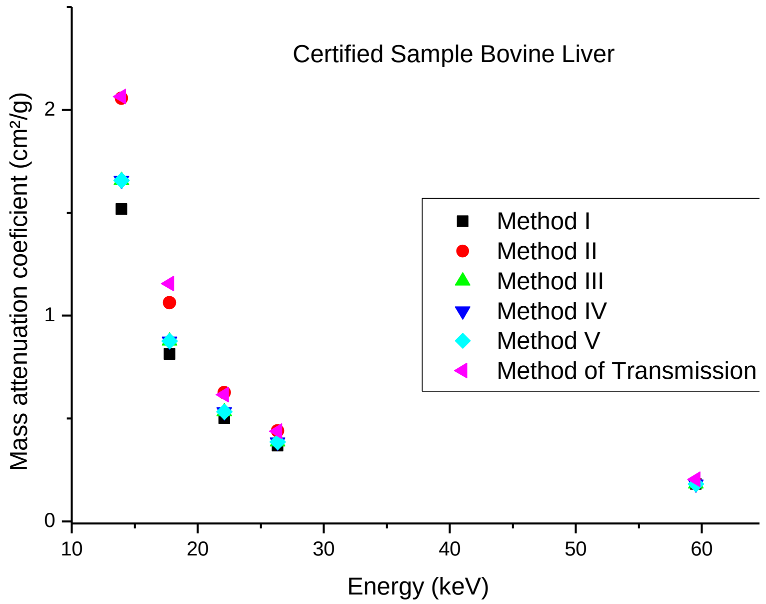

Figure 5.Mass attenuation coefficient of the sample Bovine Liver for the energies of 13.95 keV, 17.76 keV, 22.12 keV 26.36 keV and 59.54 keV.

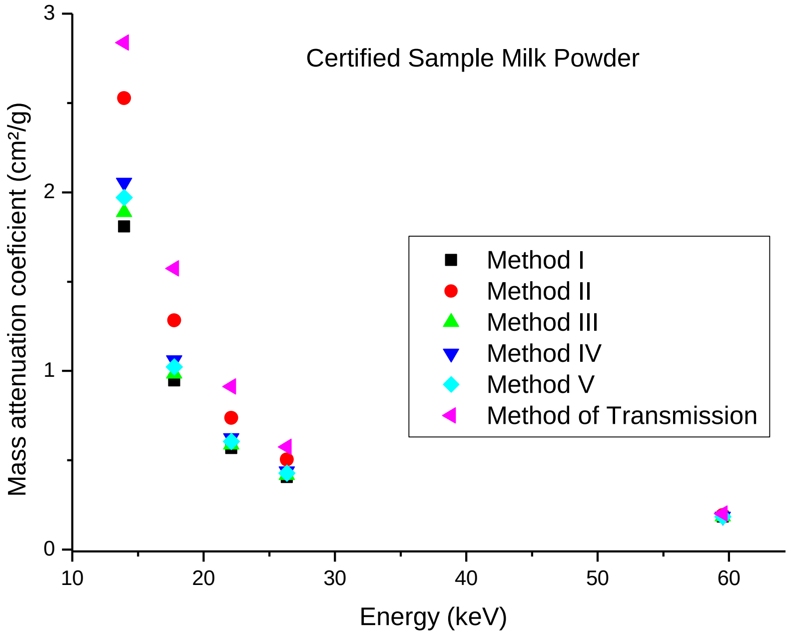

Figure 6.Mass attenuation coefficient of the sample Milk Powder for the energies of 13.95 keV, 17.76 keV, 22.12 keV 26.36 keV and 59.54 keV.

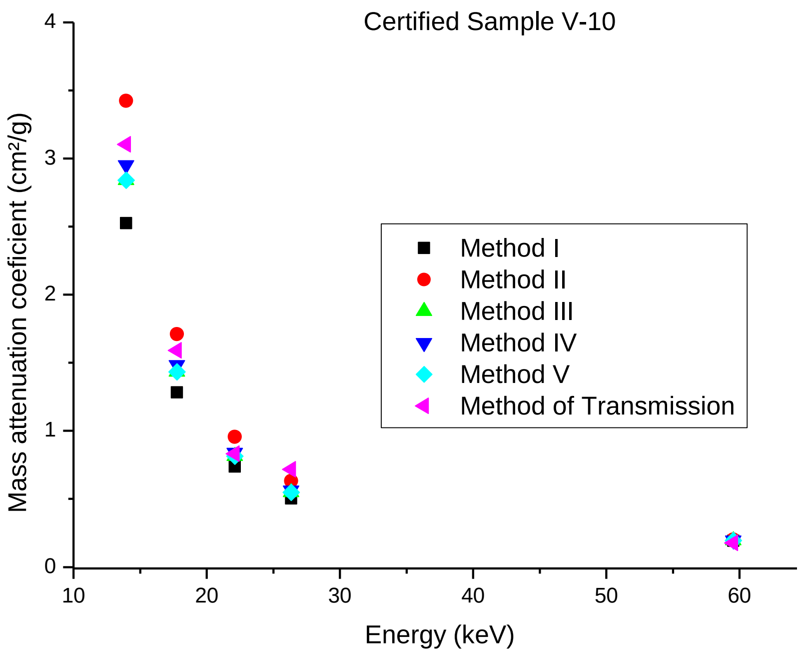

Figure 7.Mass attenuation coefficient of the sample V-10 for the energies of 13.95 keV, 17.76 keV, 22.12 keV 26.36 keV and 59.54 keV.

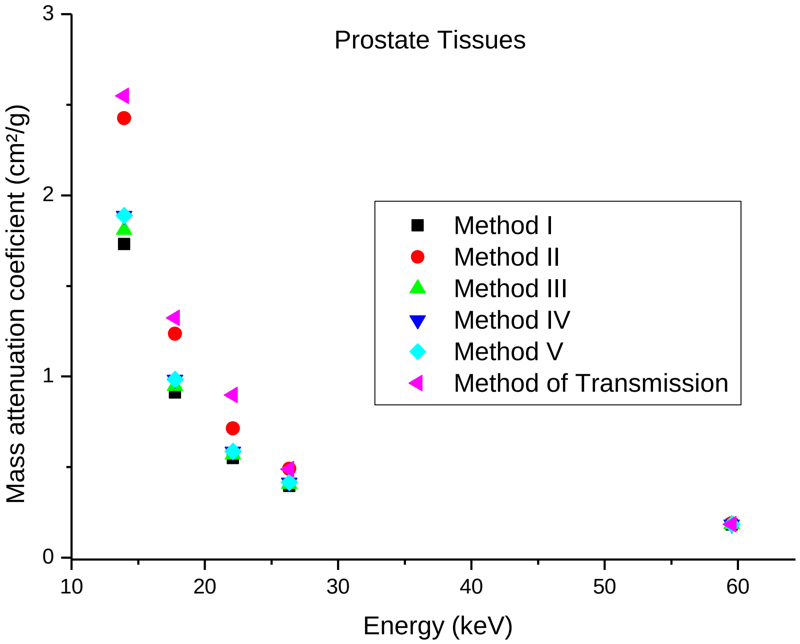

Figure 8.Mass attenuation coefficient of the sample Bovine Liver for the energies of 13.95 keV, 17.76 keV, 22.12 keV 26.36 keV and 59.54 keV.

The results found compared to the method of transmission results show the feasibility of the technique presented. Comparing the five methods of calculation of the effective atomic number, we can check that the values found by the method II are closer to the values found by the method of transmission. This is because the calculation of the effective atomic number by method II considers the interaction of radiation with the sample through momentum transferred.

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