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# Correction of radiation absorption on biological samples using Rayleigh to Compton scattering ratio

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ABSTRACT

The aim of this work was to develop a method to correct the absorbed radiation (the mass attenuation coefficient curve) in low energy ($E < 30$ keV) applied to a biological matrix based on the Rayleigh to Compton scattering ratio and the effective atomic number. For calibration, scattering measurements were performed on standard samples of radiation produced by a gamma-ray source of $^{241}$Am (59.54 keV) also applied to certified biological samples of milk powder, hay powder and bovine liver (NIST 1557B). In addition, six methods of effective atomic number determination were used as described in literature to determinate the Rayleigh to Compton scattering ratio (R/C), in order to calculate the mass attenuation coefficient. The results obtained by the proposed method were compared with those obtained using the transmission method. The experimental results were in good agreement with transmission values suggesting that the method to correct radiation absorption presented in this paper is adequate for biological samples.



## 1. Introduction

The mass attenuation coefficient ($\mu/\rho$) is an important parameter that describes the interaction of high-energy electromagnetic radiation with matter through photoelectric absorption, Compton scattering, Rayleigh scattering and pair production. For photon energies below 1 MeV the major interaction processes considered are incoherent (Compton) scattering, coherent (Rayleigh) scattering and photoelectric absorption.

The knowledge of mass attenuation coefficients of X-ray and gamma photons in biological material is of significant interest for industrial, biological, agriculture and medical applications such as dosimetry, radiography and computerized tomography [1,2].

The mass attenuation coefficient provides a wide variety of information about fundamental properties of matter in the atomic and molecular level. It measures the interaction probability of incident photons in matter per mass and area unit [2]. Several studies in literature seek accurate measurements of the mass attenuation coefficient of building materials [3,4], metal alloys, mineral samples [5,6], and biological samples such as bone, muscle and fat [7].

Experimental techniques to obtain the mass attenuation coefficient basically use the measure of the attenuation of the transmitted beam and the density of the sample. This method is called transmission method in this paper and is the direct application of the Beer–Lambert equation. However, biological samples with small thickness attenuate the transmitted beam very little and the application of transmission techniques is not possible. An alternative for this experimental limitation could be the study of the radiation scattered by the sample to characterize the mass attenuation coefficient.

The measurement of the Rayleigh to Compton scattering ratio (R/C) between peaks produced by the sample is an alternative to the transmission method. Some works in literature use this technique for scattering tomography [8,9] and the determination of effective atomic number [10–12].

The parameter "effective atomic number" helps visualizing many physical characteristics of a material with a single number. The effective atomic number is a useful mean for the interpretation of the attenuation of X-ray or gamma radiation by a complex medium such as a biological tissue. Studies on the interaction of low energy photons with biological samples are especially important for X-ray fluorescence and X-ray diffraction.

The method presented in this paper is based on the assumption that the radiation absorption by the sample can be represented by a power function of the energy $E$ of the incident radiation on a biological matrix ($6 \leqslant Z \leqslant 15$ and $E < 30$ keV). This study proposes the development of a method for the determination of mass attenuation coefficients in samples with low atomic number based on

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Rayleigh to Compton scattering ratio and the effective atomic number.

## 2. Theorical considerations

In the interaction of low-energy photons with firmly bound electrons, it may occur that the atom absorbs all the backtracking and the photon practically loses no energy, simply changing its direction. This kind of interaction is called coherent, elastic or Rayleigh scattering. The direction of the scattered photons after Rayleigh interaction process is predominantly with low scattering angles [13]. The scattering of electrons bound to the atom is done correcting the Thomson cross section for the free electron, considering the interference possibility of scattered radiation. This correction appears as a Fourier transform of the charge density, known as form factor [14]:

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

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 scattered in a different direction from the original photon. The photon transfers energy and momentum to the electron [15]. The Compton cross section is given by:

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

where KN refers to Klein–Nishina cross section for a free electron at rest, while the incoherent scattering function $S(x,Z)$ corrects the fact that the electron is actually bound to an atom in movement.

Rayleigh and Compton scatterings are functions of the parameters form factor $F(x,Z)$ and the scattering function $S(x,Z)$, which depend on the momentum transfer $x$ and on the atomic number. Thus, for a given momentum transfer, functions $S$ and $F$ depend only on the atomic number.

For mixtures, the cross section ratio depends only on the effective atomic number $Z_{\text{eff}}$, which is a complicated function of the atomic number of each component present in the sample [18]. Therefore, knowing the Rayleigh to Compton scattering ratio, it is possible to obtain the radiation absorption curve for a specific type of sample.

### 2.1. Attenuation coefficient

When a beam of gamma radiation is 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 a function of the intensity $I_0$ of the incident beam, the Beer–Lambert law, which is valid for a monoenergetic radiation beam [15]:

$$I = I_0 \cdot e^{-\mu_m \cdot \rho \cdot D} \tag{3}$$

where $\mu_m$ is called the mass attenuation coefficient and $\rho$ represents the density of the medium.

For biological matrixes or low atomic number materials ($6 \leqslant Z \leqslant 15$) and low energies ($E < 30$ keV) the mass attenuation coefficient $\mu_m$ can be represented by a power function of energy $E$ of the incident radiation through the expression:

$$\mu_m = AE^B \tag{4}$$

where $A$ and $B$ are constants.

Applying natural logarithm on both sides of Eq. (4):

$$\ln(\mu_m) = \ln(A) + B\ln(E) \tag{5}$$

Eq. (5) is a linear function between ln ($\mu$) and ln ($E$). So, constants $A$ and $B$ can be obtained by a simple linear regression analysis.

The XCOM database was used to obtain the mass absorption coefficients of the samples. XCOM is a widely used program that calculates photon cross sections for scattering, photoelectric absorption and pair production, as well as total attenuation coefficients, in any element, compound or mixture, in an energy range from 1 keV to 100 GeV [16].

The transmission method used in this study consists in experimentally determining the mass attenuation coefficient through the Beer–Lambert law. This method was applied for the energies 13.95, 17.74, 22.12 and 26.36 keV.

### 2.2. Determination of effective atomic number

It is possible to use reference samples with well defined composition to obtain the curve that expresses the relation between $R/C$ and $Z_{\text{eff}}$ of reference samples, which is then used to determine $Z_{\text{eff}}$ of an unknown sample. Recent studies show that there is not a well defined relation to calculate the effective atomic number $Z_{\text{eff}}$ of a composite material. Therefore, there are different approaches to calculate the effective atomic number of a sample composed of several elements.

Six methods for determining the effective atomic number were found in literature and are described below:

#### 2.2.1. Method I

In the first method, Harding et al. [17] assumes that the Rayleigh to Compton scattering ratio is a power function of the effective atomic number:

$$R = K \cdot (Z_{\text{eff}})^A \tag{6}$$

where $K$ represents the ratio between Thomson and Klein–Nishina cross sections and $A$ is a power of $Z_{\text{eff}}$. We can assume that the Rayleigh and Compton scatterings are proportional to $Z^3$ and $Z$, respectively [18]. Thus, the equation of the effective atomic number can be written as:

$$Z_{\text{eff}} = \left[\frac{\sum (w_i/A_i) \cdot Z_i^3}{(w_i/A_i) \cdot Z_i}\right]^{1/2} \tag{7}$$

#### 2.2.2. Method II

The method proposed by Duvauchelle et al. [19] uses the atomic form factor $F(x,Z)$ and the incoherent scattering function $S(x,Z)$, that depend on the atomic number and on the momentum transfer $x$. For each value of momentum transfer there is a discrete function $f_x$ that provides the value of $Z$ as a function of $F^2/S$.

$$Z = f_x^D\left(F^2/S\right) \tag{8}$$

For a sample composed of various elements, it is possible assume that the $f_x$ functions are continuous so that the $Z_{\text{eff}}$ value can be calculated through the following equation:

$$Z_{\text{eff}} = f_x\left[\frac{\sum \alpha_i^{\text{at}} \cdot [F(x,Z_i)]^2}{\sum \alpha_i^{\text{at}} \cdot S(x,Z_i)}\right] \tag{9}$$

$$Z_{\text{eff}} = f_x\left[\left(F^2/S\right)_{\text{eff}}\right] \tag{10}$$

Equation $f_x$ can be obtained through an appropriate curve. In this way the value of $Z_{\text{eff}}$ can be determined from the value of $(F^2/S)_{\text{eff}}$ of the sample in consideration.