Effective atomic numbers and electron density of dosimetric material

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ABSTRACT

A novel method for determination of mass attenuation coefficient of x-rays employing NaI (TI) detector system and radioactive sources is described in this paper. A rigid geometry arrangement and gating of the spectrometer at FWHM position and selection of absorber foils are all done following detailed investigation, to minimize the effect of small angle scattering and multiple scattering on the mass attenuation coefficient, \( \mu/\rho \), value. Firstly, for standardization purposes the mass attenuation coefficients of elemental foils such as Aluminum, Copper, Molybdenum, Tantalum and Lead are measured and then, this method is utilized for dosimetric interested material (sulfates). The experimental mass attenuation coefficient values are compared with the theoretical values to find good agreement between the theory and experiment within one to two per cent. The effective atomic numbers of the biological substitute material are calculated by sum rule and from the graph. The electron density of dosimetric material is calculated using the effective atomic number. The study has discussed in detail the attenuation coefficient, effective atomic number and electron density of dosimetric material/biological substitutes.

Key words: Mass attenuation coefficient, effective atomic number, electron density, dosimetric materials

Introduction

In medical physics it is important to evaluate the amount of radiation, delivered by the ionizing radiation, in composite substances. The energy delivered through the photon interactions in composite substances cannot represent the atomic number uniquely across the entire energy region. This number in composite substances is called the effective atomic number and it varies with energy and is denoted here by \( Z_{\text{eff}} \). On the other hand, the concept of z-dependence of photon attenuation coefficient has been utilized in many applications of radiation studies.[1] For example, precise knowledge of effective atomic numbers is very important in medical radiation dosimetry and medical imaging, where the cross-sectional anatomy is generated by computer tomography (CT) scans.[2] It is a common practice to verify the validity of calculation algorithms by comparing the generated doses with the measured doses in tissue equivalent phantom substances. Similarly, tissue-equivalent phantoms are specifically designed to study the image quality and performance of the CT scanners. In both instances, a precise knowledge of the effective atomic number and electron density of the composite substances is necessary in the low energy region and have proved to be a convenient parameter for interpretation of x-ray attenuation by a complex medium like a biological tissue and particularly in the calculation of dose in radiography and radiation dosimetry etc.[3]

The importance of this paper from diagnostic or therapeutic point of view is that while calculating the effective atomic number of the compound, especially when the photon energy is close to the binding energy of the electron present in the compound, it gives correct information about corrections to be added while calculating the dose to the patient. In such cases the experimental determined effective atomic number may not be agreeable with the theoretical values i.e. deviates from calculated values using the Jackson’s formula.

The x-ray mass attenuation coefficient, \( \mu/\rho \), for any material is usually estimated from Bragg’s additivity law or more commonly called mixture rule. Thus \( \mu/\rho \) for any chemical compound/material is given by

\[
\mu/\rho = \sum \omega_i (\mu/\rho)_i,
\]

where \( (\mu/\rho)_i \) is the mass attenuation coefficient of the \( i^{th} \) element and \( \omega_i \) is the fraction by weight of the \( i^{th} \) element.

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For a compound/material with chemical formula \((Z_1)_{a_1}, (Z_2)_{a_2}, \ldots, (Z_n)_{a_n}\) the weight factor for the \(i\)th element is given by

\[
\omega_i = \left( \frac{a_i A_i}{\Sigma a_i A_i} \right),
\]

where \(A_i\) is the atomic weight of the \(i\)th element. Hence an attempt has been made, in this regard, to determine the \(\mu/\rho\) of x-rays for the dosimetric material (sulfates of Mg, Ca, Mn, Fe and Zn elements) and then determine the \(Z_{\text{eff}}\) of these material by LSF method from \(\ln(\mu/\rho)\) Vs. \(\ln Z\) graph. These values are compared with the theoretical values. Using the these values of \(Z_{\text{eff}}\) the effective electron density calculated by the expression

\[
N_e = N_A Z_{\text{eff}} / A_{\text{eff}}
\]

Where \(N_A\) is the Avogadro’s number, \(A_{\text{eff}} = A/n\) is the effective atomic weight is the ratio of the molecular weight of the sample divided by the total number of the atoms of all types present in the compound.

**Experimental**

The good-geometry experimental arrangement used in determination of the mass attenuation coefficient is similar to the one described in detail by us earlier \cite{4} and the schematic experimental setup is shown in Figure 1. Briefly, photons from a variable energy x-ray source \(S\) passed through a collimator \(C1\) and were incident on the specimen \(A\) in the form of a thin foil/pellet kept normal to the photon beam. The transmitted beam passed through another collimator \(C2\) and reached a NaI(Tl) x-ray detector \(D\). The transmitted photon spectrum was recorded using a PC-based multi-channel analyzer.

The collimators \(C1\) and \(C2\) were 40 mm thick lead discs that collimated respectively the incident and transmitted beam to 6 mm dia. The scatter acceptance angle equal to the sum of the incident beam divergence and acceptance angle at the detector is found to be less than or equal to 3\(^\circ\) degrees. This thickness of the collimator would reduce the intensity of scattered photons of 300 keV by a factor of \(10^7\).

A radioactive isotope \(^{57}\)Co of strength 0.37 MBq (10 \(\mu\)Ci), was obtained from BRIT, Mumbai, India. \(^{57}\)Co decays by electron capture to the \(^{57}\)Ge ground state, emitting \(\beta\) \(^{57}\)Fe x-rays. The NaI(Tl) detector can’t resolve \(\beta\) and \(\alpha\) x-rays. In the present paper it is proposed that the mass attenuation coefficients are to be determined for the \(\beta\) x-ray only and removing the \(\alpha\) x-rays. Hence the \(\beta\) x-ray intensity has practically been eliminated by the differential absorption technique. So, the transmitted beam was regarded to have the weighted average energy of \(K_{\alpha 1}\) and \(K_{\alpha 2}\) i.e. \(K_{\beta}\) is 6.400 keV. Similarly, for the \(^{65}\)Zn radioactive source only 8.907 keV x-rays selected for the final measurement of mass attenuation coefficient. The variable energy x-ray source consisted of 10 mCi (370 MBq) \(^{241}\)Am as the primary source of excitation radiation and Rubidium target selected to produce fluorescence x-ray with characteristic energy of the target i.e., 13.339 keV. The inner bremsstrahlung intensity was found to be negligible compared to the x-ray intensity in the region of interest from the radioactive sources. No noticeable impurities were observed in the source spectra.

The dosimetric compounds viz., MgSO\(_4\cdot7\)H\(_2\)O, CaSO\(_4\cdot2\)H\(_2\)O, MnSO\(_4\cdotH_2O, FeSO_4\cdot7H_2O, ZnSO_4\cdot7H_2O\) of 99.5\% purity were obtained from SD fine chemicals Mumbai, India. Metal foil (Al, Cu, Mo and Ta) standards were procured from Good Fellow, England was used for standardization purposes only. The dosimetric samples of required thickness in the range of 10 to 200 mg/cm\(^2\) were prepared in the form of 10 mm dia cylindrical pellets by pressing the weighed quantity of the finely ground powder in a hand operated hydraulic press at a pressure of 10 ton. The area density (mass per unit area) of a foil/pellet sample was determined by weighing it using a single pan electronic balance with an accuracy of 0.01 mg and measuring its dimensions using a traveling microscope with an accuracy of 0.001 cm. Thus, the measured areal density expressed in mg/cm\(^2\) had an uncertainty of less than one per cent.

A bicron-made integrated assembly of 25mm dia x 4 mm thick Na(Tl) scintillation mounted on a photomultiplier tube (PMT) served as the x-ray detector. Oxford model PCAP plus PC plug-in single PCI card had on board high voltage supply, pre-amplifier, amplifier, and 1k ADC. The components on the card were individually controlled and used as 1k channel MCA using the software package OXWIN MCA.

The error involved in each measurement is taken care of by following the procedure counting time conditions.
as stated in Rose and Shapiro, viz., background to signal background to foil thickness and signal to foil thickness, systematic errors due to the detection of forward scattered radiation, beam hardening when higher atomic number absorber is used. The Ray-sum method has been adopted in the present measurement for calculation for the random errors which arises from all aspects of the measurement, further is has also suggested a method for the calculation called the ray-sum error. In the present measurements, Ray-sum method is applied to all observations since the random errors arise from all aspects of measurement, in the exponential law of attenuation. The errors presented in the tables are due to propagation of errors calculated according the formula given by Pearson and Osborne.

No dead time corrections are found for radioactive Co and Zn sources. However, in the present case we have selected the live time of the MCA for sources. With these conditions, the transmitted intensity of x-rays for various combinations of specimen thickness is recorded and conditions, the transmitted intensity of x-rays for various selected the live time of the MCA for sources. With these different material too.

The validity of the Beer-Lambert’s law. This is confirmed for a straight line for the entire transmission region, verifying transmission as a function of specimen thickness yielded the formula given by Pearson and Osborne.

The extrapolated effective atomic number values of the dosimetric material are presented in Table 2 and these values found to vary from 10.25 to 18.43 for all the sulfates. The theoretical values of the Zeff are also calculated using the formula given by Jackson and Hawkes and these values are discussed in the light of the dosimetry point of view and as discussed in the introduction. The experimental and theoretical Zeff values are agreeing within 5% except the edge region. It is important to mention that the theoretical/calculated values have not considered the edge effects and since the effective atomic numbers are under/over estimated when any element falls below the absorption edge. In the present work, there is a good indication that even in the low photon energy region say that up to 15

Results and Discussion

The plots of the logarithm of transmitted intensity versus specimen thickness were linear for all the samples and the \( \mu/\rho \) is obtained from the plots of linear regression over the 50-2% transmission range. The \( \mu/\rho \) obtained for all the dosimetric compounds at three different photon energies are presented in Table 1. The theoretical results have been calculated by WinXCom or its predecessor, XCOM using the mixture rule and theoretical \( \mu/\rho \) values of the elements. The theoretical estimated errors are lying between one to two per cent as mentioned in the WinXCom. The error involved in over all experimental values is lying between 2-3% for the dosimetric samples. The experimental \( \mu/\rho \) values are presented in second column and theoretical \( \mu/\rho \) are presented in the third column of Table 1. The percent deviation is the difference between the experimental and theoretical \( \mu/\rho \) values divided by theoretical value. The determined values of \( \mu/\rho \) in this transmission range is agreeing well with the theoretical values of WinXCom within two to three per cent. Figure 2 clearly shows that the edge effect on the mass attenuation coefficient values otherwise all the three lines would have shown linear graph with a positive slope. As energy increases, \( \mu/\rho \) decreases, which is well known fact that \( \mu/\rho \) strongly depends on the atomic number of the absorber and inversely proportional to the energy.

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### Table 1: Experimental and theoretical mass attenuation coefficient for dosimetric material

| Name of the Sample | Mass attenuation coefficient (cm²/g) | PD in % |
|--------------------|-----------------------------|--------|
| Expt. value | WinXcom | Expt. value | WinXcom |
| MgSO₄·7H₂O | 6.400 keV | 45.5±1.0 | 46.99 | -3.17 |
| CaSO₄·2H₂O | 120±1.2 | 118.8 | 1.70 |
| MnSO₄·H₂O | 65.9±0.9 | 64.4 | 2.33 |
| FeSO₄·7H₂O | 50.9±0.5 | 49.1 | 2.85 |
| ZnSO₄·7H₂O | 59.0±0.6 | 58.2 | 1.37 |
| MgSO₄·7H₂O | 8.907 keV | 34.7±0.6 | 35.4 | -1.98 |
| CaSO₄·2H₂O | 48.3±0.8 | 47.6 | 1.47 |
| MnSO₄·H₂O | 85.2±0.9 | 84.3 | 1.06 |
| FeSO₄·7H₂O | 60.5±0.8 | 59.9 | 1.00 |
| ZnSO₄·7H₂O | 23.2±0.4 | 22.9 | 1.31 |
| MgSO₄·7H₂O | 13.339 keV | 5.62±0.9 | 5.53 | 1.63 |
| CaSO₄·2H₂O | 15.9±0.2 | 15.1 | 5.30 |
| MnSO₄·H₂O | 28.2±0.3 | 27.7 | 1.80 |
| FeSO₄·7H₂O | 18.2±0.2 | 19.8 | 8.08 |
| ZnSO₄·7H₂O | 30.2±0.3 | 29.1 | 3.78 |

PD = Percent difference = \( \frac{\text{Computed } \mu/\rho - \text{Experimental mean } \mu/\rho}{\text{Computed } \mu/\rho} \times 100 \)
Table 2: Experimental and theoretical effective atomic number and electron density for dosimetric material

| Name of the sample | Effective atomic number ($Z_{eff}$) Expt | Electron density $N_e (10^{24}$ electrons g$^{-1}$) |
|-------------------|----------------------------------------|--------------------------------------------------|
| MgSO$_4$.7H$_2$O  | 7.21                                   | 0.543                                            |
| CaSO$_4$.2H$_2$O  | 10.25                                  | 0.676                                            |
| MnSO$_4$.H$_2$O   | 14.01                                  | 0.588                                            |
| FeSO$_4$.7H$_2$O  | 11.18                                  | 0.478                                            |
| ZnSO$_4$.7H$_2$O  | 10.48                                  | 0.613                                            |
| MgSO$_4$.7H$_2$O  | 10.07                                  | 0.644                                            |
| CaSO$_4$.2H$_2$O  | 13.76                                  | 0.577                                            |
| MnSO$_4$.H$_2$O   | 15.99                                  | 0.513                                            |
| FeSO$_4$.7H$_2$O  | 14.42                                  | 0.843                                            |
| ZnSO$_4$.7H$_2$O  | 10.87                                  | 0.614                                            |
| MgSO$_4$.7H$_2$O  | 10.33                                  | 0.681                                            |
| CaSO$_4$.2H$_2$O  | 14.02                                  | 0.588                                            |
| MnSO$_4$.H$_2$O   | 18.65                                  | 0.598                                            |
| FeSO$_4$.7H$_2$O  | 15.89                                  | 0.929                                            |
| ZnSO$_4$.7H$_2$O  | 18.43                                  | 1.042                                            |

At 6.400 keV the effective atomic number can be determined with greater accuracy but one should take into account of edge effects. The electron density of the dosimetric materials is calculated using the experimental $Z_{eff}$ values and found to vary 0.478 to 0.676 ($10^{24}$ electrons g$^{-1}$).

Conclusions

The experimental and theoretical $Z_{eff}$ values are agreeing within five per cent except at the edge region and the determined $Z_{eff}$ value is agreeing with the theoretical values within five per cent for three energies mentioned.

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