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Effective atomic numbers and electron densities of some human tissues and dosimetric materials for mean energies of various radiation sources relevant to radiotherapy and medical applications

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HIGHLIGHTS

- Mean energies for different radiation sources have been determined.
- Human tissues and dosimetric materials have been investigated according to different sources.
- Different methods were applied for calculation of E_{eff}, Z_{eff} and n_{eff}.

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ABSTRACT

Effective atomic numbers, Z_{eff}, and electron densities, n_{eff}, are convenient parameters used to characterise the radiation response of a multi-element material in many technical and medical applications. Accurate values of these physical parameters provide essential data in medical physics. In the present study, the effective atomic numbers and electron densities have been calculated for some human tissues and dosimetric materials such as Adipose Tissue (ICRU-44), Bone Cortical (ICRU-44), Brain Grey/White Matter (ICRU-44), Breast Tissue (ICRU-44), Lung Tissue (ICRU-44), Soft Tissue (ICRU-44), LiF TLD-100H, TLD-100, Water, Borosilicate Glass, PAG (Gel Dosimeter), Fricke (Gel Dosimeter) and OSL (Aluminium Oxide) using mean photon energies, E_m, of various radiation sources. The used radiation sources are Pd-103, Tc-99, Ra-226, I-131, Ir-192, Co-60, 30 kVp, 40 kVp, 50 kVp (Intrabeam, Carl Zeiss Meditec) and 6 MV (Mohan-6 MV) sources. The E_m values were then used to calculate Z_{eff} and n_{eff} of the tissues and dosimetric materials for various radiation sources. Different calculation methods for Z_{eff} such as the direct method, the interpolation method and Auto-Z_{eff} computer program were used and agreements and disagreements between the used methods have been presented and discussed. It has been observed that at higher E_m values agreement is quite satisfactory (Dif. $<5\%$) between the adopted methods.

1. Introduction

Since the X-rays and/or gamma rays are widely used in medical diagnostics, therapy, radiography and medical imaging, knowledge about how radiation interacts with the human body becomes very important from the point of dosimetry and radiological protection. Thus, accurate values of photon interaction parameters such as effective atomic number and electron density are required to give conclusive information on photon interaction with target material, in addition to being used as correction values (especially in calculations of dose) in medical physics. Different types of radiotherapy or medical applications require specific type of radiation sources which could emit photons that have more interaction probabilities with the target tissue, thus transfer more energy to the target. Even the kV and 6 MV photons have relatively low energies, they are of use in some radiotherapy applications. Low and medium X-rays, approximately 10–400 kV generating potential, are used clinically in external radiation therapy (Dellow, 2008). Also, as it is mentioned in the AAPM report in 2001 kilovoltage (40–300 kV) X-ray beams continue to be used in radiation therapy and radiobiology (Ma et al., 2001). Also, it has been reported that 6 MV X rays are of use in radiotherapy applications (Wang et al., 2002; Foote et al., 1996; Hussein et al., 2012). The physical working principle behind the CT scanners is

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based on the X-ray attenuation, thus accurate values of effective atomic numbers and electron densities are needed to obtain high resolution images in addition to the photon attenuation coefficients. 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 (Shivaramu et al., 2001). In this case, precise knowledge of effective atomic number and electron density is required. Literature is rich of experimental as well as theoretical studies regarding effective atomic number and electron density in which radiation sources of emitting monoenergetic X- and/or gamma-rays are used (Manjunathaguru and Umesh, 2006; Cevik et al., 2008; Manohara et al., 2009; Kurudirek et al., 2010; Polat and Icelli, 2010; Rudraswamy et al., 2010; Kurudirek, 2011; Kurudirek and Topcuoglu, 2011; Manjunatha and Rudraswamy, 2011, 2012, 2013; Han et al., 2012; Mann et al., 2012; Taylor et al., 2012; Kucuk et al., 2013; Un, 2013). Theoretical tabulations are widely available in the form of XCOM (Berger and Hubbell, 1999) and WinXCom (Gerward et al., 2004) databases which give photon interaction cross-sections and mass attenuation coefficients of elements as well as user defined compounds and mixtures for photon energies from 1 keV to 100 GeV which are of monoenergetic. In case of the energies of 1–4 keV, the discrepancies are known to reach to a value of 25–50%. Chantler (2000) has successfully addressed the huge discrepancies between the mass attenuation coefficients below 4 keV and derived new theoretical results of substantially higher accuracy in near-edge soft X-ray regions in detail (Chantler, 2000).

Due to the different photon interaction processes that give different weights to the atomic numbers and the different energy regions they pre-dominate, the multi-element materials cannot be represented by a single atomic number uniquely across the entire energy region. The number that is introduced to describe the multi element materials in terms of equivalent elements is called effective atomic number (Z_{eff}) and it varies with the photon energy. On the other hand, the effective electron density refers to the number of electrons per unit mass of a multi element material. Effective atomic number and electron density are convenient parameters used to understand the interaction of radiation with the target material better and to estimate absorbed dose accurately. Also, dosimetric materials are generally investigated with respect to their equivalent properties to that of water and tissue in terms of radiation interaction parameters i.e., effective atomic number and electron density. Recently, Qi et al. (2010) have developed a novel computed tomography (CT) imaging technique and they used this technique to obtain effective atomic number and electron density (Qi et al., 2010). In the light of the growing interest in the use of MV cone beam computed tomography in radiotherapy treatment planning, accurate values of electron density of the tissues are required to compute dose distributions accurately (Hughes et al., 2012). There are several studies with respect to the use of electron density in radiotherapy applications as well as medical imaging (Constantinou et al., 1992; Kanematsu et al., 2012; Seco and Evans, 2006; Nobah et al., 2011)

Studies on effective atomic number and electron density of multi element materials for multi energetic photon beams are of very scarce. In the present study, effective atomic numbers and electron densities for human tissues as well as dosimetric materials have been calculated for different radiation sources emitting photons of different energies. Determination of E_m as well as Z_{eff} and n_{eff} for composite materials are of importance since they could give prior knowledge in how radiation interacts with matter before dosimetric applications. Also, different alternative methods have been presented i.e., the interpolation method, the direct method and Auto-Z_{eff} computer program in order to show agreements and disagreements between them. Since they have merits and demerits upon the considered materials and the interested energy range, the parameters were calculated using each method. They have been discussed in detail in the further sections of this paper. The procedure for each method has been explained in the following section in detail. The all selected materials and radiation sources are available in Auto-Z_{eff} program. It would be interesting to compare the direct and interpolation methods with the Auto-Z_{eff}program for possible agreements and disagreements for the available radiation sources.

2. Calculation method

2.1. Mean photon energy

Mean photon energies for the used radiation sources have been calculated using the following relation based on ratios of photons per disintegration (emission rate) from the radiation source:

$$E_m = \frac{\sum_i w_i E_i}{\sum_i w_i} \tag{1}$$

where w_i is a branching ratio of each emitted photon of different energy, E_i is the energy of the ith photons having the w_i branching ratio. In the case of kVp and MV X-Rays, the mean photon energies have been calculated using the data provided within the Auto-Z_{eff} program.

2.2. Effective atomic number

The following approaches have been used to calculate Z_{eff} of the given materials for different radiation sources:

2.2.1. Direct method

The following relation has been used to obtain the effective atomic numbers:

$$Z_{eff} = \frac{\sum_i w_i f_i A_i (\mu/\rho)_i}{\sum_i f_j (A_j/Z_j)(\mu/\rho)_j} \tag{2}$$

where f_i is the fraction by mole of the each constituent element providing that $\sum_i f_j = 1$, A_i is the atomic weight, Z_j is the atomic number, $(\mu/\rho)_i$ is the mass attenuation coefficient (Manohara et al., 2008a). In this method, the quantities are directly used in the relation without employing any additional interpolation or fitting procedure. The detailed explanation on this method can be found elsewhere (Manohara et al., 2008a).

2.2.2. Interpolation method

The total atomic cross section can be obtained by dividing the mass attenuation coefficient μ/ρ (cm^2/g) of the material by the total number of atoms present in one gram of that material as follows:

$$\sigma_a = \frac{(\mu/\rho)_s}{N_A \sum_i w_i / A_i} \text{ (barns/atom)} \tag{3}$$

where $(\mu/\rho)_s$ is the mass attenuation coefficient of the sample, N_A is the Avogadro constant, w_i is the fraction by weight of the element i, and A_i is the atomic weight of the ith element.

WinXCom computer program has been used to calculate the total mass attenuation coefficients of the materials. Total mass attenuation coefficient and atomic cross section data as well as partial cross sections for photon atom interactions such as photoelectric, Compton scattering etc. can be obtained for about 100 elements at energies from 1 keV to 100 GeV using this program (Gerward et al., 2004). The total atomic cross section values of samples were then interpolated in the total atomic cross section values of elements generated from WinXCom (Gerward et al., 2004) at the selected energy to calculate the effective atomic number (Z_{eff}) using the following logarithmic interpolation