Results in Physics 5 (2015) 228–234

Contents lists available at ScienceDirect

Results in Physics

journal homepage: www.journals.elsevier.com/results-in-physics

Determining the mass attenuation coefficient, effective atomic number, and electron density of raw wood and binderless particleboards of *Rhizophora* spp. by using Monte Carlo simulation

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ARTICLE INFO

Article history:
Received 16 July 2015
Accepted 24 August 2015
Available online 31 August 2015

Keywords:
Effective atomic number
Effective electron density
Rhizophora spp. wood
MCNP5
XCOM

ABSTRACT

Rhizophora spp. wood has the potential to serve as a solid water or tissue equivalent phantom for photon and electron beam dosimetry. In this study, the effective atomic number (Z_{eff}) and effective electron density (N_{eff}) of raw wood and binderless *Rhizophora* spp. particleboards in four different particle sizes were determined in the 10–60 keV energy region. The mass attenuation coefficients used in the calculations were obtained using the Monte Carlo N-Particle (MCNP5) simulation code. The MCNP5 calculations of the attenuation parameters for the *Rhizophora* spp. samples were plotted graphically against photon energy and discussed in terms of their relative differences compared with those of water and breast tissue. Moreover, the validity of the MCNP5 code was examined by comparing the calculated attenuation parameters with the theoretical values obtained by the XCOM program based on the mixture rule. The results indicated that the MCNP5 process can be followed to determine the attenuation of gamma rays with several photon energies in other materials.

Introduction

Materials used as solid water and tissue equivalent phantoms have to exhibit radiological characteristics similar to those of water. Hence, the tissue-equivalence for photon beams can be ensured by checking the total mass attenuation coefficient (μ_m), effective atomic number (Z_{eff}), and effective electron density (N_{eff}) [1,2]. Numerous experimental and theoretical investigations have been conducted to determine the interaction parameters of X-rays and γ-rays with elements, compounds, and mixtures. These studies aimed to determine the values of μ_m and Z_{eff} [3–5] to represent the attenuation of radiation in compounds and mixtures, as well as in dose calculations in radiation therapy [6]. The accurate values of radiation interaction parameters in several materials are invaluable in many applied fields of science, such as nuclear and radiation physics, radiation protection and dosimetry, nuclear diagnostics and nuclear medicine, as well as agricultural, environmental, and industrial studies. Hubbell and Seltzer [7] tabulated the μ_m in a wide energy range (1–20 MeV) for all elements ($Z = 1$ to 92) and 48 additional substances of dosimetric interest. As an alternative technique, Berger and Hubbell [8] developed a computer program named XCOM for calculating the attenuation coefficients of elements, compounds, and mixtures in a wide range of photon energies. Gerward et al. [9] converted this program to the Windows platform and named it WinXcom. This program is based on the mixture rule for calculating the partial and total mass attenuation coefficients for all standard elements and mixtures and selected energies.

Rhizophora spp. is a type of mangrove wood that exhibits the characteristics of ionizing radiation interaction similar to those of water, as well as similarities in radiometric properties with other standard phantom materials in radiation dosimetry [10–13]. However, the natural wood of *Rhizophora* spp. suffers from a number of drawbacks, such as inhomogeneity of density and propensity to grow mold, and it becomes slimy, warped, and cracked with time, which limit its use as a tissue-equivalent phantom material. Hence,

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http://dx.doi.org/10.1016/j.rinp.2015.08.009
2211-3797/

binderless *Rhizophora* spp. particleboard is preferable than raw wood because of its accessibility to be fabricated easily into homogenous slabs without cracks [11,14]. In the current study, the photon interaction for *Rhizophora* spp. wood is evaluated. The effective atomic number (Z_{eff}) and effective electron density (N_{eff}) of raw *Rhizophora* spp. wood and *Rhizophora* spp. binderless particleboard in four different particle sizes, as well as that of pure liquid water and young-age breast tissue, are calculated in the energy range from 10 keV to 60 keV. The mass attenuation coefficients used in these calculations are obtained using the Monte Carlo N-Particle (MCNP5) simulation code. The obtained data are compared with the theoretical values calculated using the XCOM program based on the mixture rule. The dependencies of these parameters among the investigated samples over the photon energy considered, as well as the relative differences, are examined and discussed accordingly.

The values of Z_{eff} and N_{eff} in the 10–60 keV energy region of *Rhizophora* spp. wood classified as a tissue equivalent material have not been reported. Banjade et al. [10] reported an estimated average value of 7.09 for Z_{eff} of *Rhizophora* spp. wood, but did not consider the variation over energy. Thus, we conducted this study as a sequel to the work conducted by Marashdeh et al. [12]. The present calculations are performed on the same composite materials of the previous study, but in a wider range of energy (10–60 keV). The present work is important because accurate values of attenuation parameters are necessary to establish the regions of validity of theory-based parameterization, in addition to providing essential data in such diverse fields as tomography, X-ray and γ-ray fluorescence studies, and radiation biophysics.

Theory

The interaction of radiation with matter is important in radiation, nuclear, medical, biophysics, and other applied sciences. The probability of photon interaction by one physical process or another per unit distance traveled is called the linear attenuation coefficient or macroscopic cross section and is denoted by μ_ℓ. The mass attenuation coefficient μ_m is a density independent coefficient, which is a measure of the degree of absorption or scattering of radiation by a chemical species or substance at a given wavelength per unit mass. The coefficient μ_m (in $cm^2\,g^{-1}$) is obtained by dividing μ_ℓ by the density ρ of the absorber material. A collimated beam of radiation penetrating a material with mass-per-unit-area x is attenuated according to the exponential absorption law, Eq. (1) [15]:

$$\frac{I}{I_o} = e^{-(\mu_\ell/\rho)x} = e^{-\mu_m x} \tag{1}$$

where I_o and I are, respectively, the intensity of un-attenuated and attenuated radiation in the absorber medium. Then Eq. (1) can be rewritten as:

$$\ln\left(\frac{I_o}{I}\right) = \mu_m x \tag{2}$$

Eq. (2) is a linear equation for the mass-per-unit-area x of the target, and the mass attenuation coefficient μ_m is thus directly obtained as the slope of this straight line. According to Nordfors criteria [16], the optimum range of attenuation coefficients should match to satisfy the condition ($0.5 < \mu_\ell x < 5.0$).

Attenuation of X-rays and γ-rays in matter is related to density and atomic number. The effective atomic number (Z_{eff}) of compounds and composite materials plays a crucial role in representing the attenuation of X-rays and γ-rays [5], particularly for dose calculations in radiation therapy [4]. This parameter has gained considerable interest in terms of radiation interaction with composite materials. Z_{eff} can be calculated based on knowledge of the total atomic cross-section σ_a for materials that can be obtained from the measured values of μ_m using the following relation, Eq. (3) [17]:

$$\sigma_a = \frac{\mu_m A_r}{N_A} \tag{3}$$

where N_A is the Avogadro's number ($6.022045 \times 10^{23}\ mol^{-1}$), and A_r is the relative atomic mass of the compound and is given by $A_r = \frac{\sum_i n_i A_i}{\sum_i n_i}$. The total electronic cross-section σ_e for the element is expressed by the following Eq. (4) [18]:

$$\sigma_e = \frac{1}{N_A}\sum_i \frac{f_i N_i}{Z_i}(\mu_m)_i = \frac{\sigma_a}{Z_{eff}} \tag{4}$$

where f_i denotes the fractional abundance of the element i with respect to the number of atoms, Z_i is the atomic number of the element i. Then, the effective atomic number Z_{eff} of the material can be defined as the ratio by Eq. (5):

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \tag{5}$$

Effective electron number or electron density N_{eff}, i.e., the number of electrons per unit mass, can be calculated through the Eq. (6):

$$N_{eff} = \frac{N_A}{N} Z_{eff} \sum n_i = \frac{\mu_m}{\sigma_e} \tag{6}$$

Methods and materials

The values of the attenuation parameters were calculated in the energy range 10–60 keV for the investigated samples of natural raw and binderless *Rhizophora* spp. particleboards in four different particle sizes. The chemical composition and detailed information of the investigated samples are given elsewhere [12]. The binderless *Rhizophora* spp. particleboards were fabricated to obtain four different-sized particles with a target density of 1 g/cm^3. The particle sizes of the *Rhizophora* spp. samples are as follows: A (>147 μm), B (147–74 μm), C (74–50 μm), and D (<50 μm). Detailed information on the samples are shown elsewhere [11]. In addition, sample E is the *Rhizophora* spp. raw wood. The weight fractions of hydrogen, carbon, oxygen, and nitrogen in samples A, B, C, and D are 0%, 48.32%, 47.9%, and 3.78%, respectively. The weight fractions of the same elements in Sample E are 5.41%, 40.16%, 54.4%, and 0.03%, respectively. Finally, the maximum errors in the attenuation coefficients were calculated from the errors with different physical parameters associated with the present calculations; the estimated error of less than 4% was achieved.

MCNP5 is a general Monte Carlo code that can be used for neutron, photon, and electron or coupled neutron/photon/electron transport [19]. The MCNP5 input file simulates the experimental setup by using cell and surface cards in the input file. The MCNP5 output of the experimental setup is shown in Fig. 1. The photon mode is also considered in this simulation. The source (SDF) card was simulated to have a disk-shaped surface with 3 mm diameter and located 7 cm away from the end of the sample.

The elemental composition of the samples in the experimental setup was defined in the input file under the data cards. The detector shielding was designed in the form of a cylindrical lead collimator housing the detector with a diameter of 3 mm. The distances between (source–sample) and between (sample–detector) were 70 and 89 mm, respectively, as obtained experimentally by Marashdeh et al. [12]. The diameter of the samples was 1.34 cm. The transmitted beam of the photons was estimated for different