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Effective atomic numbers (Z_{eff}) of based calcium phosphate biomaterials: a comparative study

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HIGHLIGHTS

- Measure of the transmitted x-rays spectra using based calcium phosphate biomaterials as attenuators.
- Determination effective atomic number using four dental biomaterials.
- Determination of the mass attenuation coefficient (μ/ρ) of the biomaterials samples calculated by the WinXCOM software.
- Determination of the chemical composition of calcium phosphate biomaterials.

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ABSTRACT

This study determined the interaction of radiation parameters of four biomaterials as attenuators to measure the transmitted X-rays spectra, the mass attenuation coefficient and the effective atomic number by spectrometric system comprising the CdTe detector. The biomaterial BioOss® presented smaller mean energy than the other biomaterials. The μ/ρ and $Z_{\mathbf{eff}}$ of the biomaterials showed their dependence on photon energy. The data obtained from analytical methods of x-ray spectra, μ/ρ and $Z_{eff,}$ using biomaterials as attenuators, demonstrated that these materials could be used as substitutes for dentin, enamel and bone. Further, they are determinants for the characterization of the radiation in tissues or equivalent materials.

1. Introduction

Studies on the interaction of low energy photons with biological samples have shown to be relevant for diagnostic radiology, medical radiation dosimetry, radiation shielding and other radiation applications (Han and Demir, 2009; Kerur et al., 2009; Morabad and Kerur, 2010).

In diagnostic radiology, the radiation interaction probability is a strong function of the x-ray energy; therefore, the knowledge of the energy spectral distribution of the x-ray beam allows improving the radiographic imaging system and optimizing it for reducing doses in patients undergoing examinations (Maeda et al., 2005; Zenóbio and Silva, 2007; Zenóbio et al., 2011a).

Characteristics of radiation interactions in a tissue and in equivalent materials have been compared based on the photon mass attenuation coefficient (μ/ρ) and the coefficient of energy absorption or the effective atomic number (Z_{eff}), which it was introduced to describe the properties of composite materials in terms of equivalent elements (Singh and Badiger, 2014).

Advances in bioceramic materials have significantly contributed to the development of modern health care industry and to the improvement of the quality of human life. In dentistry, alveolar bone regeneration procedures based on calcium phosphate biomaterials have shown to be effective; such materials became a proper choice for replacements of teeth, repairs for periodontal disease, maxillofacial reconstruction, augmentation and stabilization of the jawbone. Bioceramic materials differ in composition and in physical properties among each other and additionally to the bone; this must be taken into consideration for efficient bone ingrowth and adaption with the presence of biomaterials (Legeros, 2002; Dalcusi et al., 2003; Tadic and Epple, 2004)

Theoretical and experimental investigations have been carried out with organic and inorganic materials for low energy photons

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aiming specific medical and technological applications (Içelli and Erzeneoglu, 2004; Morabad and Kerur, 2010; Koç and Ozyol, 2000; Yang et al., 1987). Nevertheless, reports concerning the use of based calcium phosphate biomaterials as attenuation materials were not found in the literature.

The aim of this work was to study the dosimetric characteristics of different calcium phosphate based biomaterials used in dentistry in order to identify if they can be used as a replacement tissue for enamel, dentin and bone as far the x-ray image in dental radiology.

2. Materials and methods

Four based calcium phosphate bone substitute biomaterials BioOss®, Cerasorb® M Dental, Osteogen®, Straumann® Boneceramic were obtained directly from the manufactures in powder form in sealed vials. Their chemical compositions were determined by the technique of Neutron Activation Analysis (INAA), Elemental Analysis (EA), Mass Spectrometry Inductively Coupled Plasma (ICP/AES) and X-ray Fluorescence (EDX). These analyses are complementary to determine all composition to each biomaterial analysed (Zenóbio et al., 2011b).

The samples of the biomaterials were prepared to obtain a 10 mm diameter cylindrical pellets by pressing the weighed amount of the finely ground powder in a Universal Instron 5882 – 100 kN device at a pressure of 100 MPa; the thickness of the samples ranged from 0.181 cm to 0.297 cm.

The procedure adopted for determination of the mass attenuation coefficient (μ/ρ) was described by Nagabhushan et al. (2004) and afterward by Kerur et al. (2009); Morabad and Kerur (2010) and Zenóbio et al. (2011b). Nagabhushan et al. (2004), to obtain highly reliable results for the photon energy range, they also recommended experimental configuration consisting of a monochromator, collimators, sample normal to the incident beam and solid detector coupled to the multichannel analyzer as the most suitable one. A good geometry set up avoids scattered photon reaching the detector is used for transmission measurement. The measurements were performed three times for each samples. The geometrical arrangement employed is shown in the Fig. 1.

Diagnostic radiology beam qualities RQR3, RQR5, RQR7 that are defined by 61,267 standard International Electrotechnical Commission Standard (IEC, 2005), were established in a 7 mm beryllium window constant potential HS320 Isovolt Pantak Seifert industrial X-ray machine. Tungsten collimators with diameter aperture of 1 and 0.4 mm were placed inside the 35 mm-long spacer (Kit EXVC). X-ray energy spectra were measured with XR-100T model CdTe detector at 150 cm from the focal spot;

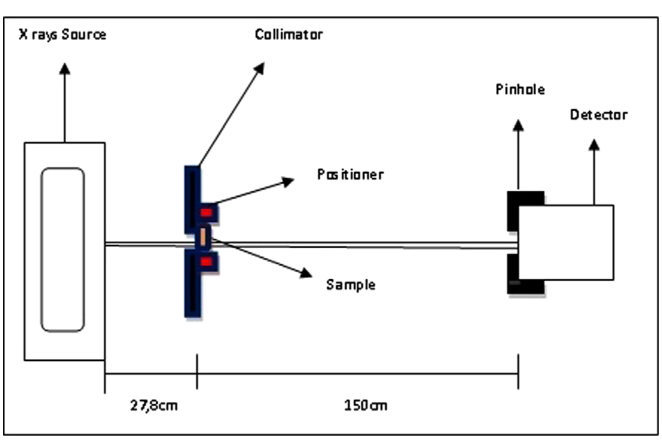

Fig. 1. Experimental set-up.

irradiation conditions were chosen to assure that pile-up effect was avoided. The experimental mass attenuation coefficients for the different materials and energies are determined by the intensity transmitted. The exponential law determines the narrow beam X-ray mass attenuation coeficiente and the process is described by the following equation:

$$I = I_0 e^{\mu m t} \quad (1)$$

where I_o denotes the photons intensity with energy, intensity without attenuation; I the photons with energy after attenuation; $\mu_m = \mu/\rho$ (cm^2/g) is the mass attenuation coeficiente and t (g/cm^2) is sample mass thickness (the mass per unit área). The measured spectra were corrected by the response function of the detector using the stripping procedure implemented using a Matlab program (Santos et al., 2015).

The theoretical values of mass attenuation coefficient (μ/ρ), for materials composed of various elements, one may assume that the contribution of each element to the total interaction of the photon is additive "Mixture Rule". In accordance with this rule, the total mass attenuation coefficient of a composite is the sum of the weight proportion of each individual atom present in it (Morabad and Kerur, 2010). Therefore:

$$\left(\frac{\mu}{\rho}\right)_{comp} = \sum (W_i)\left(\frac{\mu}{\rho}\right)_i \quad (2)$$

In which: $(\mu/\rho)_{comp}$ is the mass attenuation coefficient for the composite, $(\mu/\rho)_i$ is the mass attenuation coefficient of each individual element and w_i is the fractionated weight of the elements in the composite. The weight fractions of each element present in the biomaterials samples were determined by analytical means mentioned above.

The procedure of calculation the effective atomic number by direct method has been described elsewhere El-Khayatt and Al-Rajhi (2015) and Manohara et al. (2009) and can be expressed in terms of effective cross section per atom, σ_a, and an effective cross-section per electron, σ_e by the following equation:

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} = \frac{\sum_i W_i A_i \left(\frac{\mu}{\rho}\right) i}{\sum_i w A_i \left(\frac{\mu}{\rho}\right) i} \quad (3)$$

The Z_{eff} values were determined directly for total interactions within a radiological low photon energy range, from 33.96 to 46.43 keV (Polat and Içelli, 2010; Manohara, 2009; Ozdemir and Kurudirek, 2009; Yang et al., 1987; Rao et al., 1985). Atomic cross-section in barn/atom was computed from the μ/ρ using the following relation:

$$\sigma_a = \frac{\mu_c/\rho}{N \sum_i W_i/A_i} \quad (4)$$

where Ai represents atomic number of the constituent elements, while N represents the Avogadro constant (White, 1977). Plots were drawn, showing the total of atomic cross-section in the individual element present in the mixture determined by analytical technics as a function of the atomic numbers, for all photon energies considered. From these plots, the experimental Z_{eff} was obtained by linear interpolation (Shivaramu, 2002; Manohara et al., 2009).

The maximum errors in mass attenuation coefficients were calculated from errors in incident (I_0) and transmitted (I) intensities and areal density (t) and statistical counting (Ozdemir and Kurudirek, 2009).

$$\Delta\left(\frac{\mu}{\rho}\right) = \frac{1}{t}\sqrt{\left(\frac{\Delta I_0}{I_0}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\ln\frac{I_0}{I}\right)^2 + \left(\frac{\Delta t}{t}\right)^2} \quad (5)$$