Mass attenuation coefficient (μ/ρ), effective atomic number (Z_{eff}) and measurement of x-ray energy spectra using based calcium phosphate biomaterials: a comparative study

Madelon Aparecida Fernandes Zenobio[1,2], Elton Gonçalves Zenobio[3]
Teógenes Augusto da Silva [1,2], Maria do Socorro Nogueira[1,2]

[1] Development Center of Nuclear Technology- CDTN/CNEN
Avenida Presidente Antônio Carlos 6.627Campus UFMG
31270-901Belo Horizonte, Brazil. madelon@cdtn.br

[2]Postgraduate Course on Nuclear Science and Techniques, UFMG
Av. Antônio Carlos 6627 Campus UFMG
31.270-90 Belo Horizonte, Brazil. silvata@cdtn.br; mnogue@cdtn.br.

[3] PUCMINAS- Pontifíce Catholic University of Minas Gerais
Av. Dom José Gaspar 500
30535-901 Belo Horizonte, Brazil. zenobio@pucminas.br

Abstract

In dentistry, alveolar bone regeneration procedures using based calcium phosphate biomaterials have been shown effective. However,there are not reports in the literature of studies the interaction of low energy radiation in these biomaterials used as attenuator and not being then allowed a comparison between the theoretical values and experimental.The objective of this study was to determine the interaction of radiation parameters of four dental biomaterials - BioOss®, Cerasorb® M Dental, Straumann® Boneceramic and Osteogen® for diagnostic radiology qualities. As a material and methods, the composition of the biomaterials was determined by the analytical techniques. The samples with 0.181cm to 0,297cm thickness were experimentally used as attenuators for the measurement of the transmitted X-rays spectra in X-ray equipment with 50 to 90 kV range by spectrometric system comprising the CdTe detector. After this procedure, the mass attenuation coefficient, the effective atomic number were determined and compared between all the specimens analyzed, using the program WinXCOM in the range of 10 to 200 keV. In all strains examined observed that the energy spectrum of x-rays transmitted through the BioOss® has the mean energy slightly smaller than the others biomaterials for close thickness. The μ/ρ and Z_{eff} of the biomaterials showed its dependence on photon energy and atomic number of the elements of the material analyzed. It is concluded according to the methodology employed in this study that the measurements of x-ray spectrum, μ/ρ and Z_{eff} using biomaterials as attenuators confirmed that the thickness, density, composition of the samples, the incident photon energy are factors that determine the characteristics of radiation in a tissue or equivalent material.

Keywords: biomaterials, mass attenuation coefficient, X-rays spectra, effective atomic number

1.- INTRODUCTION

Studies on the interaction of low energy photons with biological samples are important in the field of diagnostic radiology, medical radiation dosimetry, radiation shielding and nuclear engineering materials showing an interdisciplinary science.

In the diagnostic radiology, the radiation interaction probability is a strong function of x-ray energy, therefore the x-ray spectral distribution should be known in order to optimize the radiographic imaging system; this would contribute to optimization and dose reduction in patients [Maeda *et al*. 2005, Zenobio and Silva 2007; Zenobio *et al*. 2011].

For a comparison of the characteristics of radiation in a tissue or equivalent material, the coefficient of mass attenuation (μ/ρ) of the photon and the coefficient of energy absorption or the effective atomic number (Z_{eff}) must be considered. Z_{eff} was introduced to describe the properties of composite materials in terms of equivalent elements [El Abd and Elkady 2014].

Advances in many specialty bioceramics have made significant contribution to the development of modern health care industry and have improved the quality of human life. In dentistry, alveolar bone regeneration procedures using based calcium phosphate biomaterials have been shown effective and are the materials of choice in replacements of teeth, repair for periodontal disease, maxillofacial reconstruction, augmentation and stabilization of the jawbone. Theoretical and experimental investigations were carried out in organic and inorganic materials in low energies presenting specific medical and technological applications [Içelli and Erzeneoglu 2004; Morabad and Kerur 2010; Koç and Ozyol 2000; Yang *et al.* 1987]. Nevertheless, there are no reports in literature concerning the use of as based calcium phosphate biomaterials attenuation materials. This fact does not allow for the establishment of comparisons between the theoretical and experimental values. However, by means of investigation of the mass attenuation coefficient (μ/ρ), effective atomic number (Z_{eff}) and measurement of x-ray energy spectra using based calcium phosphate biomaterials, invaluable information about the radiation interaction process in diagnostic radiology x-ray qualities is expected to be provide.

2.- MATERIALS AND METHODS

This work was carried out in the Development Center of Nuclear Technology laboratories, Brazil. Four bone substitute materials: BioOss®, Cerasorb® M Dental, Osteogen®, Straumann® Boneceramic and Osteogen® were obtained directly from the manufactures in sealed vials in the powder form. 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) following well established procedures.

The samples of the based calcium phosphate biomaterials were prepared in the form of 10mm diameter cylindrical pellets by pressing the weighed amount of the finely ground powder in a Universal Instron 5882 - 100kN device at a pressure of 100 MPa. The thickness of the Bio-Oss®, Cerasorb® M Dental, Osteogen®, Straumann® Boneceramic range of 0.181cm to 0,297cm. The satisfactory geometrical arrangement has been employed (Figure 1). Diagnostic radiology beam qualities RQR3, RQR5, RQR7 that are defined by 61267 International Electrotechnical Commission Standard (IEC, 2005), were established in a 250 mm beryllium window constant potential Isovolt HS320 Pantak Seifert industrial X-ray machine and 1 and 4mA tube current ranges [Kerur 2009; Zenobio *et al*. 2011]. 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; irradiation conditions were chosen to assure that pile-up effect was avoided. In this research, the theoretical values of the mass attenuation coefficient (μ/ρ) of the biomaterials samples were calculated by the WinXCOM software. 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” [Morabad and Kerur 2010]. 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:

$$\left(\frac{\mu}{\rho}\right)_{comp} = \sum(W_i)\left(\frac{\mu}{\rho}\right)_i \tag{1}$$

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 Z_{eff} values were determined directly for total interactions within a radiological low photon energy range, from 10 to 200 keV [Özdemir and Kurudirek 2009; Rao *et al*. 1985; Yang *et al*. 1987]. The atomic cross-section in barn/atom was computed from the μ/ρ using the following relation:

$$\mu_a = \frac{\mu_c/\rho}{N\sum_i W_i/A_i} \tag{2}$$

where Ai represents atomic number of the constituent elements, while N represents the Avogadro constant [White, 1977]. Plots were drawn between the atomic cross-section in the individual element and the atomic numbers of the elements for each energy level. From these plots, the Z_{eff} of each material was obtained by interpolation.

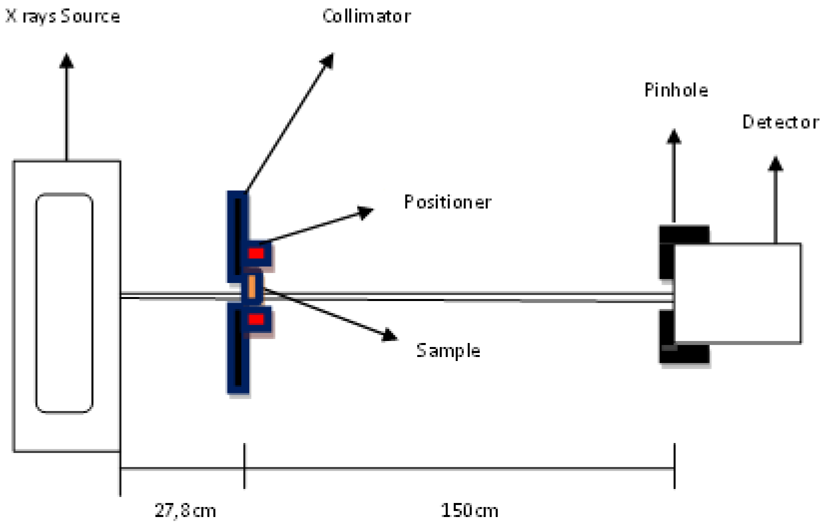

Figure 1.- Experimental set-up

3.- RESULTS AND DISCUSSIONS

The chemical composition of based calcium phosphate biomaterials that were obtained by analytical techniques are given in the Table 1. The samples presented different chemical compositions and high and different concentrations of Ca, P and organic material.

Table 1- Chemical composition of based calcium phosphate biomaterials.

Elements	Bio-Oss®	Cerasorb M Dental	Straumann Boneceramic®	Osteogen®
H	0,38		0,03	0,39
C	1,12		0,12	0,23
O	37,99	38,85	41,42	39,83
Na	1,96	2,00	0,50	1,60
Mg	0,30	0,08	0,28	
Al	0,40	0,32	0,36	0,38
Si	1,20	1,37	1,21	1,26
P	16,71	17,69	17,58	17,88
S	0,21	0,17	0,33	0,20
Cl	0,15	0,10	0,05	0,06
K		0,03	0,02	

Ca	39,59	39,39	38,10	38,17

Figures 2 to 4 show the x-ray spectra of transmitted beams through different thicknesses of biomaterials samples for the 50, 70 and 90 kV. In this experiment the average energy varied from 33.96 to 46.43 keV. Results show that the transmitted spectra have slightly differences in the penetration power and in the spectral distribution. It was clear in the Figure 4, for the 90kV. The transmitted spectrum for the Straumann® Boneceramicand and Cerasorb® M Dental show that the their mean energy is higher than the Bio-Oss® and Osteogen® even for close thicknesses.

The table 2 shows variation of the experimental and theoretical mass attenuation coefficient (μ/ρ), atomic cross-sections (μ_a) and effective atomic numbers (Z_{eff}) of the biomaterials samples with the energy. The value of the μ/ρ of the samples of biomaterials were inversely proportional to the energy in agreement studies of Morabad and Kerur [2010] and Koç and Ozyol [2000]. In this study there were significant differences between experimental and theoretical values (5.1 to 35.6%) for all biomaterials samples when evaluatted the μ/ρ, μ_a. However, in relation to the Z_{eff} the experimental results are, in general, consistent with theoretical data (0.9 to 6.2%) that were calculated using the independent atomic model, or in other word, mixture rule which theoretical value has done by considering the cross-section for isolated atom. Besides, Straumann ® Boneceramic and Cerasorb® M Dental show μ/ρ experimental and theoretical values were higher than those of Bio-Oss® and Osteogen®. These indicate that Straumann ® Boneceramic and Cerasorb® M Dental are better absorber than of Bio-Oss® and Osteogen®.

Experimental data were not found in the literature to compare with, nevertheless Zenobio [2011], Içelli and Erzeneoglu [2004] found that the uncertainties in the sample thicknesses and elemental composition of materials affected experimental results during transmitted spectrum measurements of material compounds for determining effective atomic numbers. According to Han and Demir [2009] at low photon energies the process of photoelectrical interaction and the dependence of atomic number is dominant when there is interaction of photon with matter. The discrepancies in the effective atomic number may be reduced by considering the molecular, chemical, or crystalline environment of the atom [Içelli, 2008; Singh and Badiger, 2014]. The density is additional influence factors and in biomaterial the calcination and sintering processes need to be considered when the density is evaluated [Kim *et al.* 2003]. These biomaterials, as well as enamel, dentin, bone, present in their composition high and different concentration of Ca and P; consequently, their interactions with low energy photons are expected to be different from other biological samples in agrement the literature [Lakamaa and Rytomaa 1977; Koç and Ozyol 2000; Zenobio et al. 2011]. Thus, deep knowledge of the purity of the elemental materials, the composition of alloys or mixtures is required in order to obtain accurate experimental and accurate calculated values [Zenobio et al. 2011; Kucuk et al. 2013].

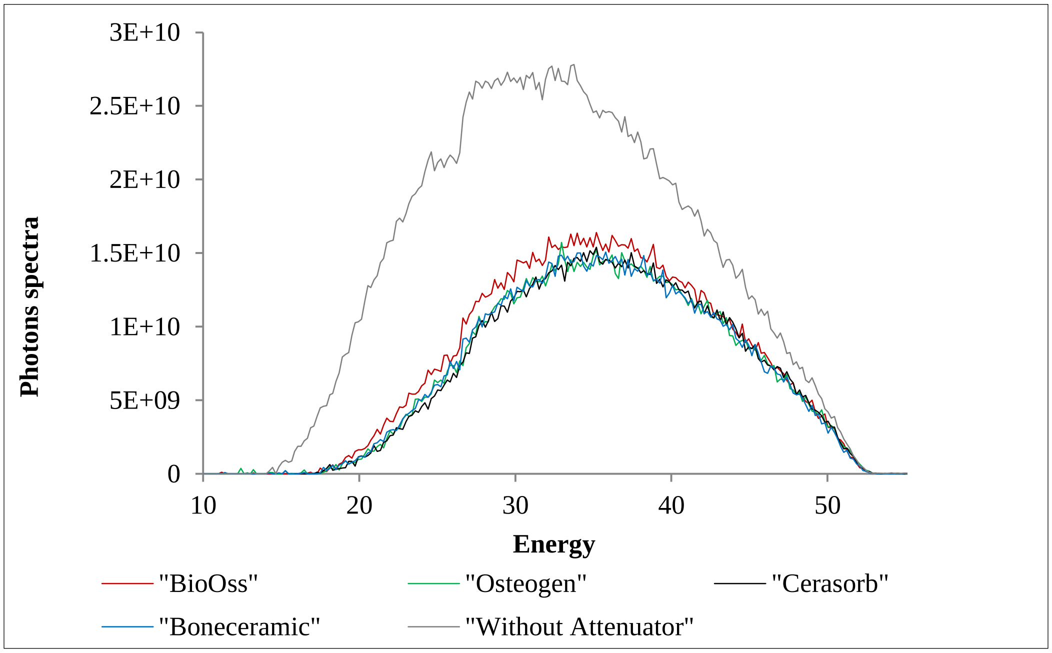

Figure 2.- Photons spectra of 50 kV x-ray beam transmitted through different thicknesses of biomaterials.

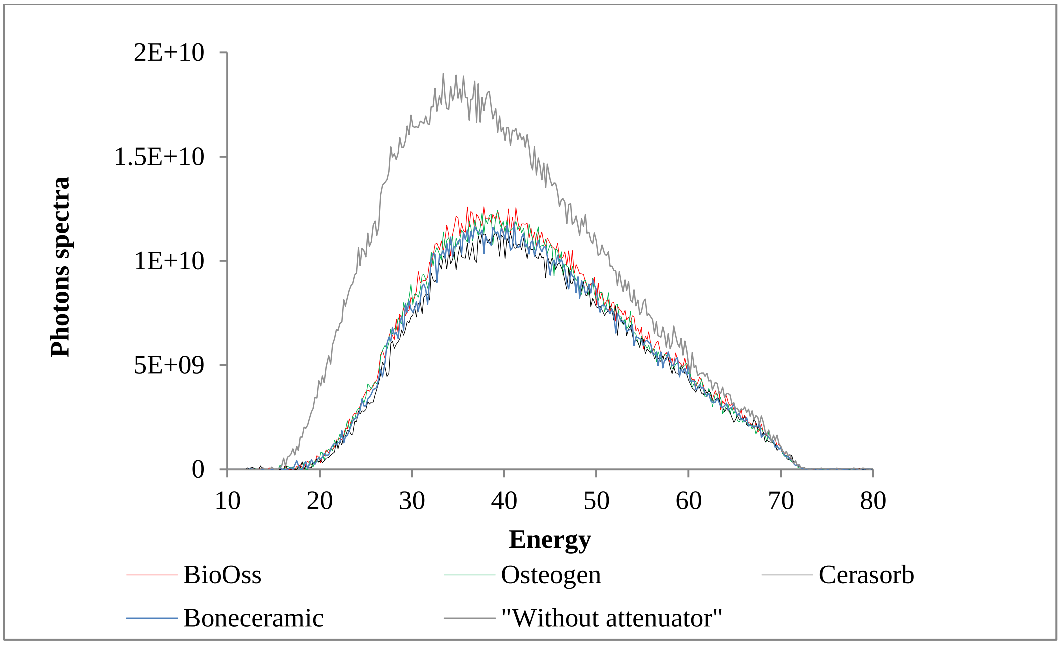

Figure 3.- Photons spectra of 70 kV x-ray beam transmitted through different thicknesses of biomaterials.

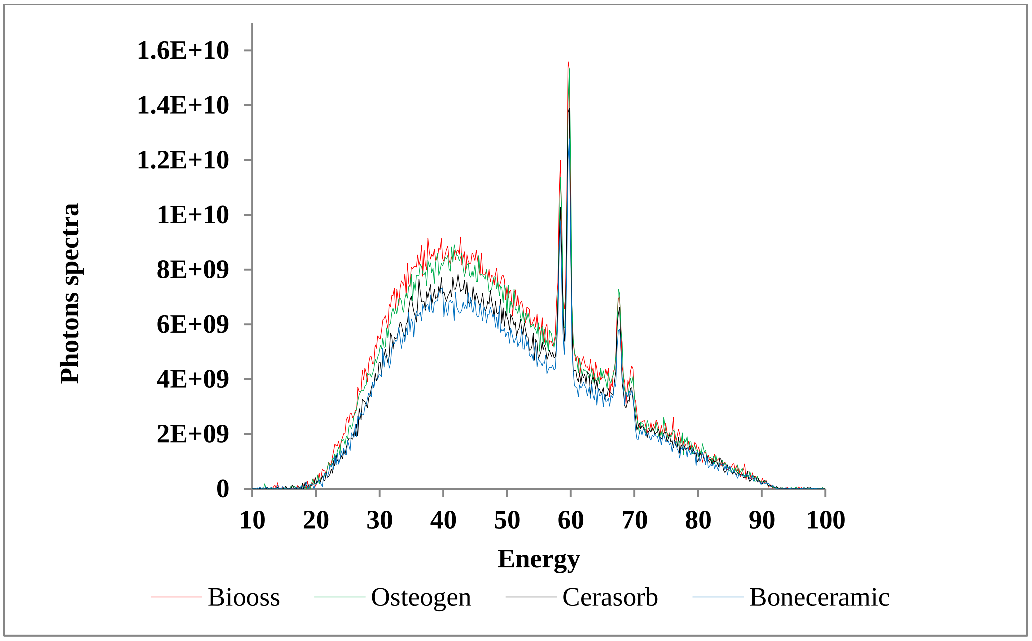

Figure 4.- Photons spectra of 90 kV x-ray beam transmitted through different thicknesses of biomaterials

Table 2.- Experimental and theoretical mass attenuation coefficient (μ/ρ), atomic cross-sections (μ$_a$), effective atomic numbers (Z$_{eff}$) of biomaterials

Biomaterials	Energy keV	$(\mu/\rho)_{Exp}$	$(\mu/\rho)_{Th}$	μ_{aExp}	μ_{aTh}	Z_{effTh}	Z_{effExp}
Bio-Oss®	34,08	1.18	1.49	70.2	55.6	1.92	1.85
	40,70	0.71	0.94	44.6	33.5	1.68	1.70
	46,17	0.48	0.67	33.0	22.8	1.79	1.58
Osteogen®	33,96	1.15	1.47	54.08	42.36	1.83	1.75
	40,67	0.83	0.93	34.13	30.45	1.69	1.65
	44,16	0.59	0.76	28.03	21.64	1.62	1.53
Cerasorb® M Dental .	34.19	1.30	1.44	57.51	51.93	1.85	1.82
	41.03	0.95	0.91	36.16	37.99	1.71	1.72
	46.35	0.84	0.62	24.65	33.41	1.59	1.68
Straumann®Boneceramic	34,19	1.22	1.49	60.04	49.30	1.85	1.80
	40,94	0.89	0.94	37.87	36.06	1.74	1.73
	46,43	0.81	0.70	28,06	32.54	1.67	1.70

The experimental and theoretical mass attenuation coefficient (μ/ρ) of biomaterials are presented in the Figure 5, for comparison.

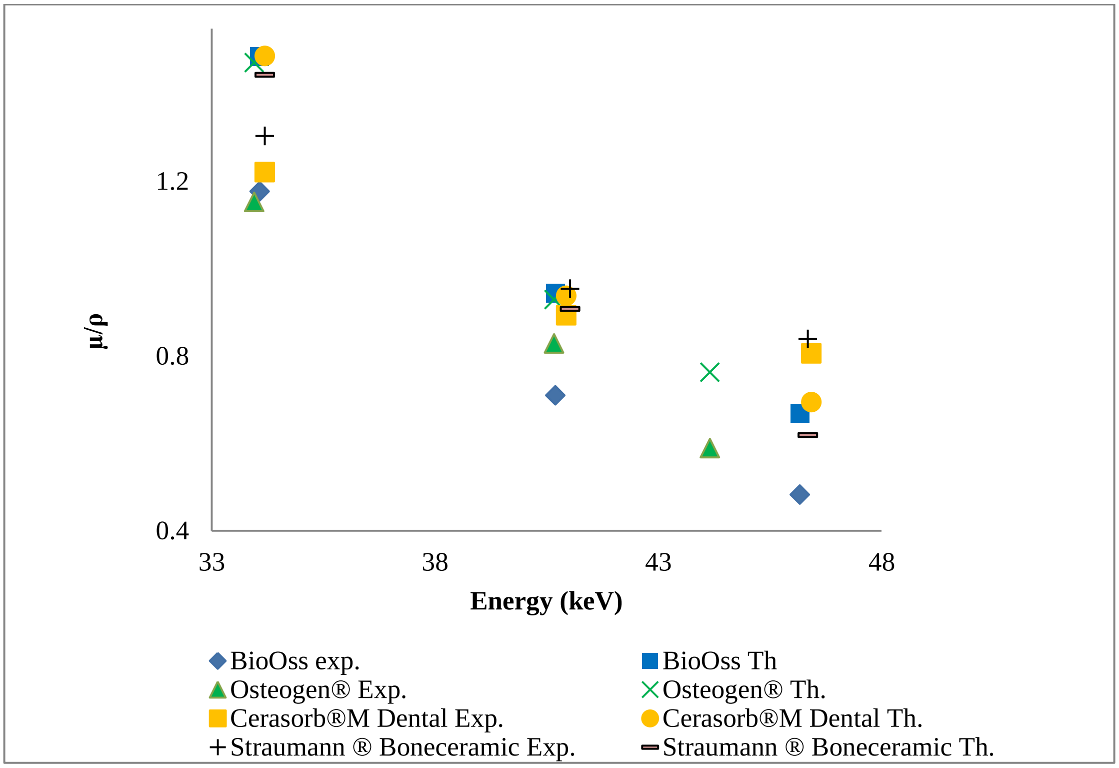

Figure 6.- μ/ρ in biomaterials samples in the present study

The mass attenuation coefficient (μ/ρ) of the biomaterials samples were calculated by the WinXCOM software. The behavior of Z_{eff} values with respect to applied energy levels for total interaction in biomaterials samples were plotted in the Figure 6, for comparison with the literature, in the energy range from 10 to 200 keV.

In the low photon energy region, the Z_{eff} decrease with the increasing of the incident photon energy. However, several jumps in values have been observed in the energy range from 30 keV to 50 keV for all materials except for the Osteogen®. Second El-Kateb *et al.* [2000] and Elmahroug *et al*. [2015] these jumps are due to the absorption K-edge of the high Z-element (Na, Al, S, Si, Ca, Mn, Fe, Zn and Sr) and this explains the differences between the values of in this region is very large compared to other regions.

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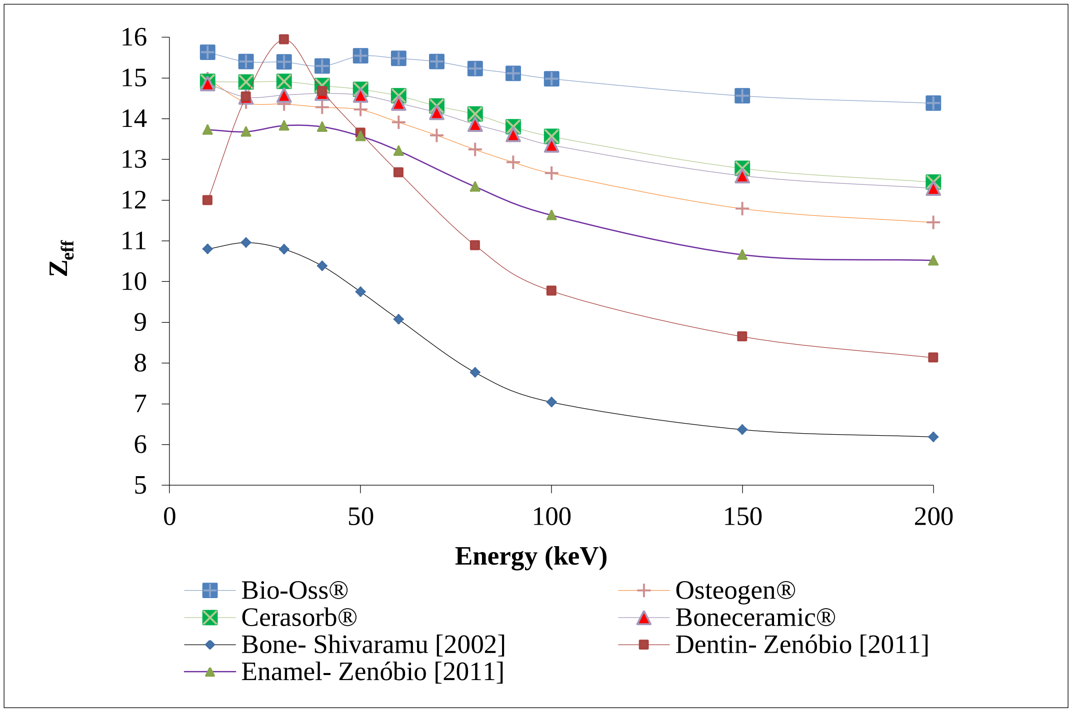

Figure 6.- Z_{eff} in biomaterials samples in the present study and the literature.

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]; given that the values estimated in this study were from 0.08% to 0.03% in the biomaterials.

5.- CONCLUSIONS

The mass attenuation coefficient (μ/ρ), effective atomic number (Z_{eff}) and measurement of x-ray energy spectra using based calcium phosphate biomaterials- Bio-Oss®, Cerasorb® M

Dental, Osteogen®, Straumann® Boneceramic- were investigated for diagnostic radiology qualities.

The measurements of x-ray spectrum, μ/ρ and Z_{eff} using biomaterials as attenuators confirmed that the thickness, density, composition of the samples, the incident photon energy are factors that determine of the characteristics of radiation in a tissue or equivalent material.

The data presented on photon interaction parameters are expected to be helpful in dosimetry; radiation shielding and other applications of radiation physics. Further investigation on the photon interaction parameters in different compounds and/or composites still remain to be done in order to confirm the validity of both.

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