Photon absorption of calcium phosphate-based dental biomaterials

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Abstract

Effective atomic number and mass energy absorption buildup factors for four calcium phosphate-based biomaterials used in dental treatments were calculated for 0.015 to 15 MeV photons. The mass energy absorption coefficients were calculated for 0.5 to 40 mean free paths of photons. In the energy region important for dental radiology the Zeff for all studied biomaterials are larger in comparison to larger energies. In x-rays for dental radiology and the energy absorption buildup factors are low, however CbMDI biomaterial shows a resonance at 80 keV.

Keywords: Biomaterials, Dental, Buildup factors, Effective atomic number.

1.- INTRODUCTION

Radiation protection and radiation physics are science and technology branches, where science and engineering merges. Scope of radiation physics is interaction of radiations (alpha, beta, gamma, neutron, etc) with living and non-living materials (biological materials, tissue materials, shielding materials, dosimeters, etc). The radiation interaction parameters with materials are being used for radiation protection and exposure control in field of nuclear technology, medical, agriculture, industries, etc. The radiation interaction covers energies for low-, medium- and high-energies.Interactions of low- and high-energy photons with biological materials samples arefound to be very crucial in the field of diagnostic radiology, medical, dosimetry, shielding and nuclear engineering. Basic photon interaction parameters i.e. mass attenuation coefficients and mass energy absorption coefficients of elements are found in literature [Sing & Badiger, 2016a;]. Photon interaction parameters for compound or mixture are calculated by mixture rule by using interaction of elements and their compositions [Yang, Leichner & Hawkins, 1987]. Similar to atomic number of an element, effective atomic number of a mixture or compound is computed using the photon interaction parameters [Singh & Badiger, 2016b].

Photoelectric effect, Compton scattering and Pair production are the main interaction mechanisms between photon radiation and atoms and nuclei of matter. The Photoelectric effect is dominant interaction process for low energy photon ($\leq$ 100 keV), Compton scattering is the dominant interaction for medium energy photons (100 keV < E < 1022keV) whereas Pair production is dominant for high energy photons ($\geq$ 1022 keV). Photoelectric effect is a complete removal process of photon, whereas pair production generates electron and positron; positron annihilates with electron producing medium energy photons. Compton effect buildups photon of medium energy through multiple scattering, which modifies the application of attenuation coefficients using Lambert Beer's law for shielding and dosimetry. Lambert's Beer law is applicable for narrow beam geometry with small thickness of sample, however for broad beam and large thickness a multiplicative factor called as buildup factor is introduced.

In dentistry field, calcium phosphate biomaterials are found to be effective materials for choice of replacements of teeth, repair for periodontal disease, maxillofacial reconstruction, augmentation and stabilization of the jawbone. Calcium phosphate is inorganic component of bone, which are used by our body to build bones and are being applied to produce biomaterials for bone repair. Several studies have been carried out in organic and inorganic materials useful in medical applications have been carried out for low-energy photons [Icelli & Erzeneoglu, 2004; Morabad & Kerur, 2010; Koç & Ozyol, 2000; Yang *et al*., 1987].

Recently, attenuation coefficients of calcium phosphate have been reported [Fernandes Zenobio *et al*., 2016]. However, the photon energy absorption and energy absorption buildup factors for biomaterials are scarce in literature.

The aim of this work was to determine the energy absorption coefficient; the effective atomic number, and the energy absorption buildup factor of calcium phosphate biomaterials for 0.015 to 15 MeV photons. The present investigation would be useful for radiation interaction process in diagnostic radiology for calcium phosphate biomaterials used in dentistry.

2.- MATERIALS AND METHODS

Chemical compositions of calcium phosphate biomaterials (CPB) for dentistry are given in Table.1. Major elemental concentration is Ca, O, and P. The mass energy absorption coefficient, μ_m^{en}, of the biomaterials is calculated using mixture rule shown in equation 1.

$$\mu_m^{en} = \sum_i^n \omega_i \left(\frac{\mu_{en}}{\rho} \right)_i \qquad (1)$$

where ω_i is the proportion by weight and $(\mu_{en}/\rho)_i$ is the linear energy absorption coefficient of the i-th element.

Table.1. Elemental compostions of calcium phosphate based dental biomaterials.

Element	Bio-Oss	Cerasorb M Dental (CbMDl)	Straumann Boneceramic (StBc)	Osteogen (Og)
H	0.38	--	0.03	0.39
C	1.12	--	0.12	0.23
O	37.99	38.85	41.42	39.83
Na	1.90	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

The effective atomic number, Z_{eff}, for compounds and mixtures is calculated using equation 2 [Manohara *et al*., 2008; Vega-Carrillo et al., 2018]. This equation was used to calculate the Z_{eff} of biomaterials using the atom fraction, f, of elements in the CPB.

$$Z_{eff} = \frac{\sum_i f_i \, A_i \, \mu_{m_i}}{\sum_i f_i \, \frac{A_i}{Z_i} \, \mu_{m_i}} \qquad (2)$$

For CPB the energy absorption buildup factors (EABF) were calculated for 0.015 to 15 MeV photons, and for penetration depths ranging from 0.015 to 40 mean free paths (mfp). Calculations were carried out using the Geometric-progression fitting parameters (G-P) for elements [ANS, 1991] in the CPB.

Buildup factors were calculated using the five-parameter fitting formula for mixtures and compound reported in the literature [Singh et al., 2017, Singh & Badiger, 2016a, Singh & Badiger, 2016b, Singh & Badiger, 2015] shown in equations 3 and 4.

$$B(E,x)=\begin{cases}1+\dfrac{b-1}{K-1}\left(K^{x}-1\right) & \text{for } K\neq 1\\ 1+(b-1)\,x & \text{for } K=1\end{cases} \tag{3}$$

$$K(E,x)=c\,x^{a}+d\,\frac{\tanh\left(\dfrac{x}{X_k}-2\right)-\tanh(-2)}{1-\tanh(-2)},\quad \text{for } x\leq 40 \text{ mfp} \tag{4}$$

Here, **E** is the photon energy, **x** is the penetration depth in mfp units, and **a**, **b**, **c**, **d** and $\mathbf{X_k}$ are the G-P fitting parameters. The value of parameter **b** IS the buildup factor to 1 mfp. The variation of the parameter **K** with the penetration depth ($\mathbf{K^x}$) represents the photon dose multiplication and the photon spectrum change.

3.- RESULTS AND DISCUSSION

The energy absorption buildup factors (EABF) are shown in Figure.1 (a)-(d), here the EABF are for 0.015 to 15 MeV photons and for different mean free paths. From Figure 1 the variation of EABF of the CPB with photon energy, it is observed that the EABF values of the CPB are highest in medium energy region (100 to 300 keV). For 60 to 80 keV photons used in dental radiology the buildup factors are lower and these values are almost independent of the mfp, this behavior is important because is the energy range of x-rays used in dental radiology, the probable explanation attributed to the interactions mechanisms between these photons and CBP, where photoelectric effect occurs with larger frequency in comparison to Compton scattering.

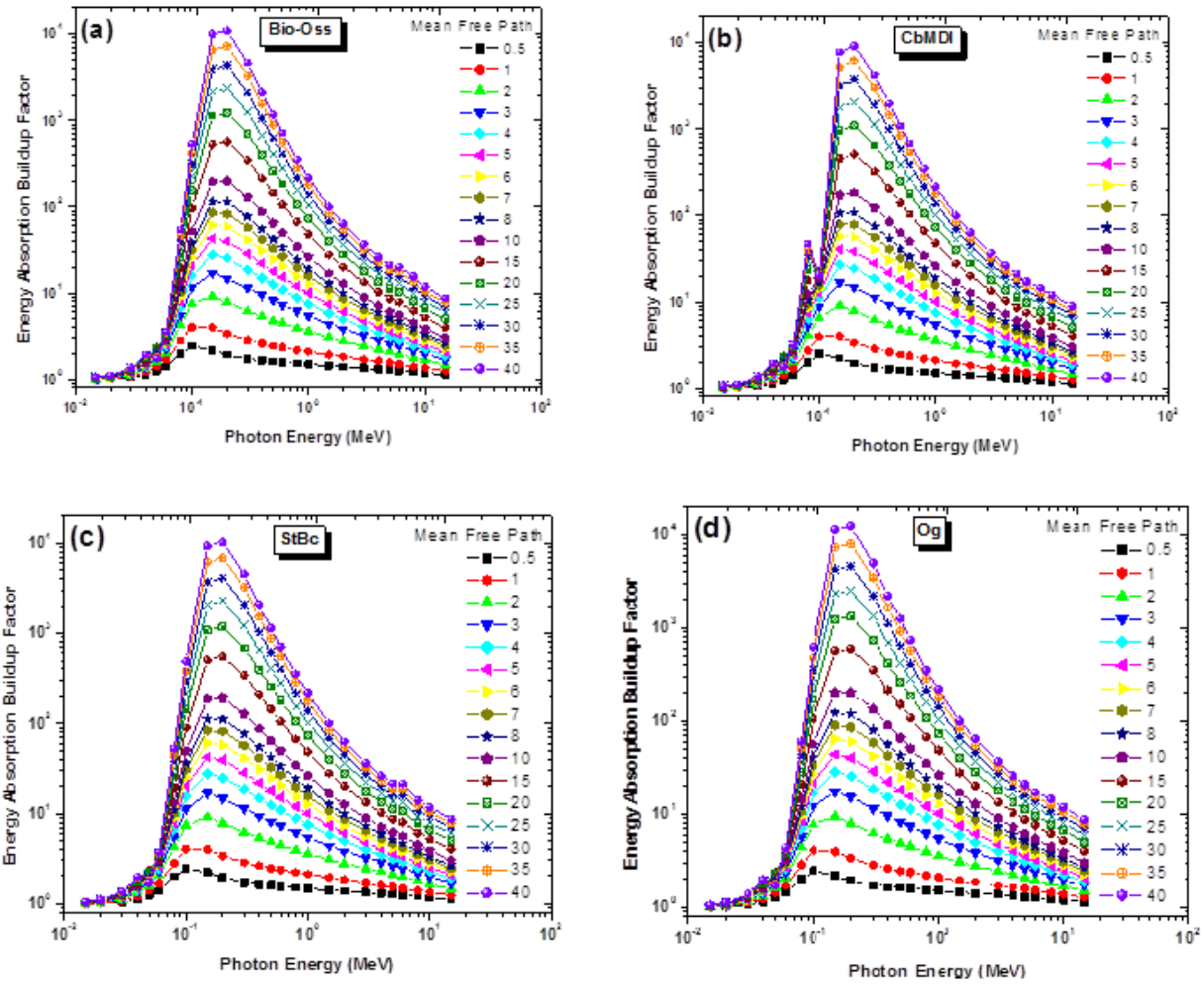

Figure 1. Energy absorption buildup factors of calcium phosphate-based dental biomaterials

The highest EABF in medium energy region are due to Compton scattering where photon buildup due to multiple scattering from constituent atomic elements of the material. This variation of EABF values with photon energy, chemical composition and mean free path can be explain using three fundamental photon interaction processes, which are available in literature elsewhere [Singh *et al*., 2016b, Singh & Badiger, 2015].

The EABF values of CPB are found of same order (peak value $\approx 10^4$) and variation are of similar nature, except CbMDl that shows a small peak around 80 keV probably due to absorption edge of Mg whose concentration is larger in CbMDI than another CPB. This

resonance is important when an oral radiography, using 80 keV photons, is used on patients having dental repairs with CBMDI.

In table 2 the effective atomic numbers of CPB for 0.015 to 15 MeV photons are shown.

Table.2. Effective atomic numbers of calcium phosphate based dental biomaterials

Energy [MeV]	Bio-Oss	CbMDl	StBc	Og
0.015	18.32	18.50	17.28	18.04
0.02	17.64	17.67	17.18	17.45
0.03	17.38	17.36	17.19	17.24
0.04	17.23	17.23	17.12	17.10
0.05	16.94	16.97	16.86	16.80
0.06	16.42	16.53	16.39	16.27
0.08	14.78	15.06	14.84	14.59
0.10	12.76	13.20	12.89	12.54
0.15	9.14	9.68	9.31	8.90
0.20	7.72	8.24	7.88	7.50
0.30	6.95	7.44	7.09	6.73
0.40	6.76	7.25	6.90	6.55
0.50	6.70	7.19	6.84	6.49
0.60	6.67	7.16	6.81	6.46
0.80	6.64	7.13	6.78	6.43
1.00	6.63	7.11	6.76	6.42
1.50	6.61	7.10	6.76	6.41
2.00	6.64	7.12	6.78	6.44
3.00	6.78	7.26	6.92	6.58
4.00	6.97	7.44	7.10	6.76
5.00	7.16	7.61	7.28	6.95
6.00	7.34	7.79	7.46	7.13
8.00	7.65	8.08	7.75	7.44
10.0	7.91	8.31	7.99	7.70
15.0	8.34	8.69	8.37	8.12

The largest Z_{eff} value is found for low energy photon and the lowest Z_{eff} is for medium energy photons. Roughly, the Z_{eff} for 0.3 to 4 MeV photons, where Compton scattering is important, is 1/3 of Z_{eff} for low energy photons (0.015 to 0.10 MeV), where Coherent scattering and photoelectric absorption are important.

4.- CONCLUSIONS

Energy absorption buildup factors and the effective atomic number have been calculated for Bio-Oss, CbMDI, StBc and Og which are calcium phosphate-based biomaterials used in dental treatments. Calculations were carried out for 0.015 to 15 MeV photons.

X-ray machines in dental radiology use voltages from 70 to 80 kV, in this energy range the energy absorption buildup factor for CbMDI biomaterial has a resonance due to the amount of Mg.

For Bio-Oss, CbMDI, StBc and Og biomaterials the Z_{eff} is larger in the energy range of X-rays used in dentistry.

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