ENERGY ABSORPTION AND EXPOSURE BUILDUP FACTORS FOR SOME BIOACTIVE GLASSES SAMPLES: PENETRATION DEPTH, PHOTON ENERGY, AND ATOMIC NUMBER DEPENDENCE

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Bioactive glasses are made of Synthetic silica-based materials and have the effect on or causing a response from living tissue, organisms or cells as implant materials to replace the diseased or damaged tissues in the human body. The present work was aimed to investigate the equivalence of some bioactive glasses samples and tissues by calculating the mass attenuation coefficient (μ/ρ), KERMA relative to air (Ka), gamma ray energy absorption buildup factors (EABF) and exposure build factors (EBF) in the energy range of 1 keV to 10 MeV. Among the selected glasses, BG4 has recorded the minimum values for the EABF and EBF, while maximum values have been detected for BG5. Results founded should be useful in clinical applications, radiotherapy, and radiation protection.

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1. Introduction

Ionizing radiation like X-ray and gamma ray causes harmful effects within living cells, tissues and organisms. The effect of ionizing radiation on human depends on many factors like types and energies of radiation, therefore, protection against these radiations is very important. Bioactive glasses are made of Synthetic silica-based materials and have the effect on or causing a response from living tissue, organisms or cells as implant materials to replace the diseased or damaged tissues in the human body. Moreover, they can be used as bone substitutes, since they can form a direct bond with human bone [1, 2].

The first bioactive glass, BG1, which mainly composed of silicon and other elements (46.1SiO2, 24.4NaO, 26.9CaO, 2.6P2O5) was proposed by Hench and co-workers in 1971 [3]. Since then, many researchers have found extensive range of clinical and dental applications such as replacement of damaged bone and tissues, dental implants for tooth fixation, joint replacements and bone implants and many more [4-7].

X-rays and Gamma rays are widely utilized in medical imaging, radiation therapy, diagnostics in nuclear medicine, mammography, and for the treatment of different diseases. Since this radiation interacts with the human body, it's energy will degraded and build up and increase secondary radiation inside the human body, this secondary radiation can be calculated by the buildup factors [8]. Therefore, when a human tissue is superseded by bioactive material, it is vital to realize how these materials can be influenced by ionized radiations in order to understand the interaction between these radiations with the bioactive glasses inside the human body.

It has been found that bioactive glasses may be suitable to be used for radiation protection and radiotherapy. Different properties, such as the mass attenuation coefficient, KERMA relative to air, gamma ray absorption buildup factor and exposure buildup factor, must be determined for an attenuator before it can be used clinically in radiation treatment or shielding. In the medical field, buildup factor is considered to be important in the distribution of photon flux and in the estimation of radiation dose received by the biological molecules. Buildup factor can be classified

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into two types: the energy absorption buildup factor (EABF) and the exposure buildup factor (EBF) [9-12].

2. Background

Buildup factors can be calculated using different methods, Geometric Progression (GP) fitting method [13], iterative method [14] and Monte Carlo method [15] is considered to be the most used methods to calculate buildup factors. American Nuclear Society ANSI/ANS-6.4.3 [16] used GP method and provides a buildup factor data for 23 elements, one compound and two mixtures versus water, air and concrete at 25 standard energies in the energy range from 15keV up to 15MeV with appropriate interval up to the penetration depth of 40 mean free path (mfp).

On the other hand, many researchers determined EABF and EBF for different materials. Sidhu et. al. [17] had computed EABF for some biological tissues, cells and bone using ANS sittings in the energy range 15keV to 15MeV and penetration depth up to 40 mfp by using GP fitting method. They found that EABF has been changed significantly with incident photon energy and effective atomic number at 15 mfp, however, the effect of the chemical composition upon the buildup factor was found negligible for energy greater than 0.5MeV.

Also, Singh et al. [18] have used GP fitting method to calculate EBF for some polymers. As reported by authors, for lower penetration depth below 10 mfp, the EBF were decreased with the increasing of the equivalent atomic number (Zeq) of the chosen polymer at all energies. Also, they found that at 15 mfp penetration depth and incident photon energy beyond 3 MeV, the EBF becomes nearly independent of Zeq of the polymers, while above 15 mfp and at incident photon energy greater than 3 MeV, a reversal in trend was observed. This indicates that the GP fitting method is useful for calculating both EABF and EBF of the bioactive glasses in this investigation.

3. Methodology

In this work, gamma ray interactions with bioactive glasses have been studied by calculating the mass attenuation coefficients (μ/ρ) in the photons energy range of 1keV up to 10MeV. KERMA relative to air (Ka) for these glasses were calculated as well. Moreover, energy absorption and exposure buildup factors were calculated using the GP fitting method for the selected glasses in the energy range from 15keV to 15MeV up to penetration depths 40 mfp.

The understanding of these properties of could be useful in choosing the appropriate sample composition that will be able to resist possible radiation and to determine the thickness and shape of the bioactive glasses needed. With an appropriate knowledge of buildup of photons in bioactive glasses, energy absorption in the human body can be carefully controlled. The results of this work may be useful in medical applications and radiotherapy. The chemical composition of the bioactive glasses employed in this work is given in Table 1 [19].

Table 1. Compositions of the investigated bioactive glasses in weight fraction

Bioactive glass	O	Na	Si	P	K	Ca
BG1	0.399	0.180	0.215	0.011	0	0.193
BG2	0.445	0	0.280	0.017	0	0.257
BG3	0.494	0	0.374	0.017	0	0.114
BG4	0.438	0	0.279	0.007	0	0.274
BG5	0.509	0	0.397	0.022	0	0.071
BG6	0.406	0.156	0.243	0.009	0.058	0.129

4. Results and discussion

4.1. Mass attenuation coefficient

The variation of the μ/ρ with the photon energy for all bioactive glass samples used in this work are shown in Fig. 1, from this figure it can be noticed that the μ/ρ values depend on the photon energy in addition to the chemical composition of glasses. Also, it can be seen that the variation of μ/ρ with the photon energy for all bioactive glasses is nearly the same. It is also clearly observed from this figure that there are three energy ranges; low (E < 50keV), intermediate (50keV< E <1MeV) and high energy region energy (E > 1MeV). These variations in μ/ρ can be interpreted using the three well-known photon scattering in the matter, whereas, photoelectric effect and pair production processes appear at the lower and high energy regions on, while Compton scattering process is dominating the intermediate energy region [20].

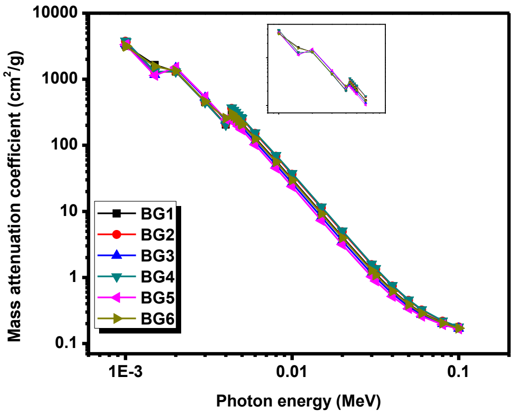

Fig. 1. Mass attenuation coefficients μ/ρ of the selected bioactive glasses with photon energy for totalphotoninteractionfrom1keVto 10MeV

In the low energy region, the values of μ/ρ of the selected bioactive glasses are very large (~3×103 cm2/g) and decrease quickly with increasing the energy. A number of jumps in μ/ρ values were observed in this energy region for all selected glasses at 1.072keV, 1.839keV, 2.145keV, 3.607keV and 4.038keV by cause of the K-edge absorption of the Na, Si, P, K and Ca elements respectively.

In the second energy region, the value of the μ/ρ for all selected bioactive glasses decreases slowly with the increment of photon energy which may be due to dominate of Compton scattering process. As it known, Compton scattering direct proportional to Z, and inversely proportional to the incident photons energy (E^{-1}). For the incident photon energy beyond 1MeV, as the photon energy increases the value of μ/ρ becomes nearly constant in the high energy region. This is due to control of pair production in this high energy region. Finally, the maximum value for μ/ρ was found for BG4, this is because BG4 contains Oxygen (O, Z=8, weight fraction =0.438%), Silicon (Si, Z=14, weight fraction =0.279%), Phosphorus (P, Z=15, weight fraction =0.007%), and Calcium (Ca, Z=20, weight fraction =0.274%). Whereas BG5 consists of Oxygen (O, =8, weight fraction =0.509%), Silicon (Si, =14, weight fraction =0.397%), Phosphorus (P, Z=15, weight fraction =0.0218%) and Calcium (Ca, =20, weight fraction =0.0714%) has the minimum μ/ρ value. It can be concluded that variation of μ/ρ depends on the weight fraction of the bioactive glasses, lower with a lower weight fraction of Calcium and vice versa.

4.2. KERMA relative to air

Fig. 2 represents the variation of Ka of the bioactive glasses with incident photon energy in the range from 1keV to 10MeV. Obviously, the value of the Ka for all bioactive glass samples increases with the increase of the photon energy and reaches the maximum at energy 50 keV. Thereafter, a rapid decrease in the Ka occurs with increasing the incident photon energy for all the bioactive glasses; and beyond 0.5MeV photon energy, the Ka of all bioactive glasses becomes constant (on order of one). Also, it is found that the Ka value of the BG4 is highest among all the bioactive glasses in the selected energy region, while the lowest value was found to BG5. The same general shape was observed for different materials such as optically stimulated luminescence (OSL) materials (Singh and Badiger, 2014) and building Materials [21].

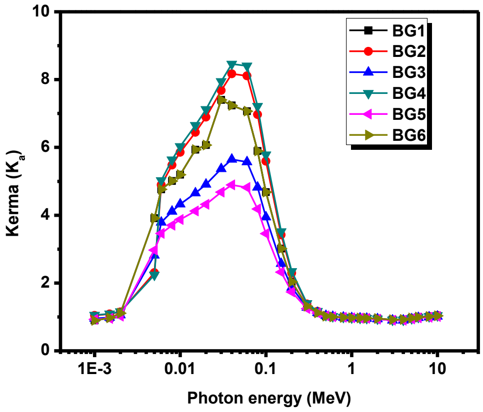

Fig. 2. Variations in kerma relative to air of bioactive glasses with photon energy in the energy range 1 KeV to 10 MeV.

4.3. Buildup factors

All bioactive glass samples equivalent atomic numbers (Zeq) and exposure GP fitting parameters were calculated in the energy range between 15keV to 15MeV are found in Tables 2-7. EABF and EBF variations for all selected bioactive glass samples have been plotted as a function of photon energy at penetration depths of 1, 5 and 10mfp, results are shown in Figs. 3 and 4. It was found that EABF and EBF values are small in both, low and high energy regions, this may be due to photoelectric effect is dominating in the low energy region and photons are totally absorbed or been removed in this region. The increasing values of EABF and EBF were found with the increasing of photon energy and have it is maximum in the intermediate energy region due to Compton scattering multiple scattering in this region. EABF and EBF values eventually start decreasing with further increasing in photon energy due to pair production in that region, same results were found by Singh et al. [22].

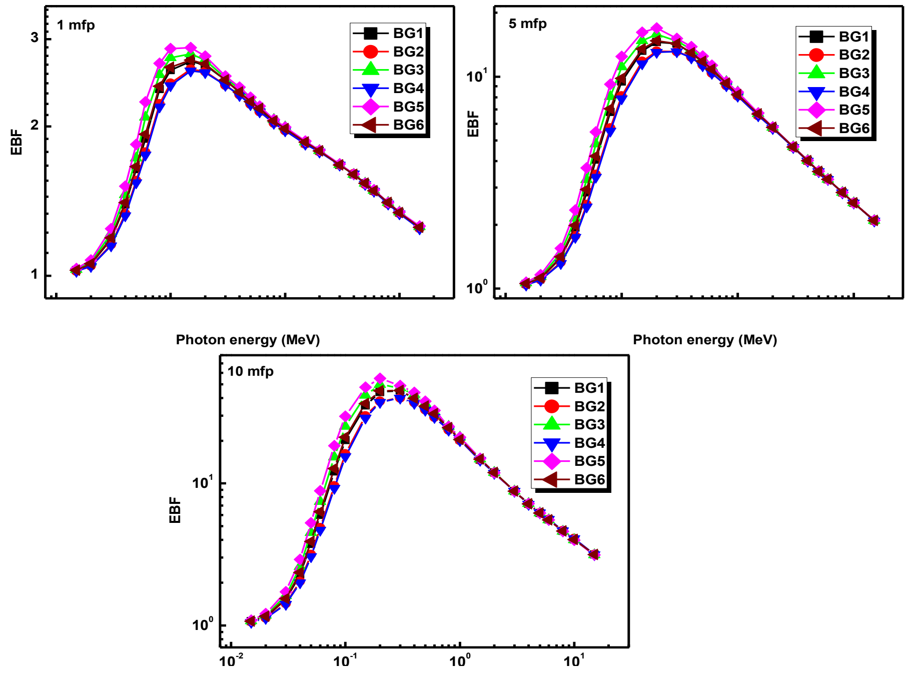

Fig. 3. Variation of exposure buildup factors with photon energy at 1, 5 and 10 mfp.

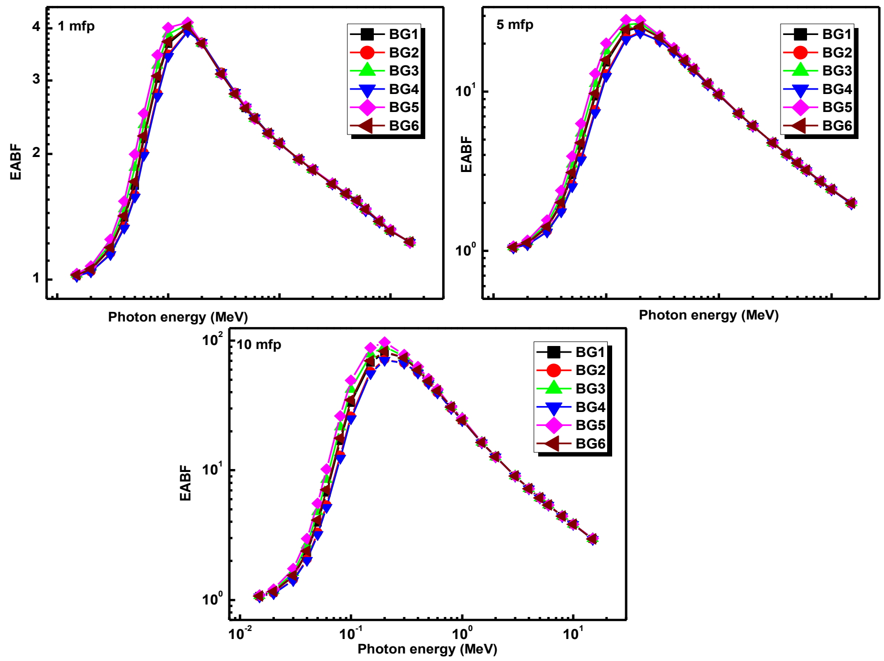

Fig. 4. Variation of energy absorption buildup factors with photon energy at 1, 5 and 10 mfp.

Table 2. Equivalent atomic number (Z_{eq}) and GP exposure (EBF) and energy absorption (EABF) buildup factor coefficients for BG1

Energy (MeV)	Z_{eq}	EBF					EABF				
		b	**c**	**a**	X_k	**d**	**b**	**c**	**a**	X_k	**d**
0.015	13.604	1.025	0.366	0.240	13.346	-0.164	1.025	0.395	0.209	12.306	-0.113
0.02	13.728	1.055	0.415	0.190	16.627	-0.111	1.057	0.406	0.195	16.744	-0.113
0.03	13.851	1.185	0.399	0.213	14.150	-0.115	1.187	0.398	0.214	14.351	-0.116
0.04	13.936	1.391	0.463	0.187	14.358	-0.105	1.407	0.457	0.188	14.624	-0.104
0.05	13.999	1.640	0.579	0.135	15.121	-0.071	1.677	0.604	0.119	16.848	-0.060
0.06	14.044	1.887	0.699	0.093	15.267	-0.052	2.169	0.601	0.140	13.566	-0.078
0.08	14.101	2.380	0.830	0.061	14.481	-0.051	3.029	0.810	0.067	13.941	-0.051
0.1	14.146	2.598	1.006	0.015	13.713	-0.031	3.673	1.011	0.013	13.758	-0.028
0.15	14.216	2.706	1.256	-0.039	10.677	-0.008	4.022	1.327	-0.056	15.287	0.008
0.2	14.160	2.662	1.366	-0.056	7.936	-0.006	3.683	1.490	-0.084	14.658	0.022
0.3	14.017	2.482	1.468	-0.078	16.929	0.014	3.110	1.581	-0.100	14.445	0.029
0.4	14.312	2.345	1.462	-0.079	16.251	0.015	2.789	1.557	-0.097	14.781	0.028
0.5	14.372	2.241	1.447	-0.078	16.304	0.017	2.578	1.527	-0.094	15.034	0.028
0.6	14.446	2.163	1.420	-0.076	17.656	0.020	2.438	1.487	-0.089	14.978	0.027
0.8	14.030	2.052	1.384	-0.073	15.291	0.021	2.242	1.424	-0.081	15.084	0.027
1	14.020	1.980	1.323	-0.063	15.836	0.018	2.124	1.358	-0.071	14.981	0.024
1.5	13.359	1.850	1.230	-0.048	15.683	0.017	1.940	1.244	-0.052	14.595	0.019
2	12.377	1.785	1.154	-0.033	15.805	0.010	1.834	1.163	-0.035	14.602	0.012
3	12.227	1.674	1.062	-0.012	15.157	-0.002	1.696	1.061	-0.012	13.843	0.000
4	12.246	1.600	0.991	0.007	12.817	-0.011	1.606	0.992	0.006	14.025	-0.009
5	12.270	1.536	0.945	0.022	10.373	-0.020	1.545	0.928	0.027	13.339	-0.026
6	12.205	1.483	0.934	0.024	12.078	-0.020	1.472	0.930	0.025	15.342	-0.029
8	12.227	1.403	0.906	0.033	13.857	-0.028	1.379	0.910	0.032	12.473	-0.024
10	12.231	1.340	0.890	0.040	13.076	-0.033	1.309	0.915	0.031	14.506	-0.027
15	12.204	1.251	0.852	0.056	14.381	-0.050	1.230	0.842	0.059	14.168	-0.053

Table 3. Equivalent atomic number (Z_{eq}) and GP exposure (EBF) and energy absorption (EABF) buildup factor coefficients for BG2.

Energy (MeV)	Z_{eq}	EBF					EABF				
		B	**c**	**a**	X_k	**d**	**b**	**c**	**a**	X_k	**d**
0.015	14.365	1.021	0.367	0.243	11.991	-0.160	1.021	0.409	0.198	11.477	-0.096
0.02	14.501	1.046	0.429	0.177	15.698	-0.092	1.046	0.418	0.187	15.571	-0.102
0.03	14.635	1.155	0.394	0.214	14.260	-0.115	1.155	0.392	0.218	14.059	-0.121
0.04	14.727	1.333	0.445	0.193	14.403	-0.108	1.342	0.443	0.193	14.647	-0.106
0.05	14.784	1.556	0.532	0.156	14.780	-0.086	1.595	0.542	0.148	15.579	-0.079
0.06	14.836	1.774	0.644	0.113	14.861	-0.062	2.015	0.546	0.163	13.678	-0.086
0.08	14.902	2.223	0.765	0.082	13.103	-0.051	2.795	0.735	0.093	13.565	-0.064
0.1	14.939	2.445	0.945	0.030	14.045	-0.040	3.467	0.930	0.034	13.695	-0.040
0.15	15.005	2.610	1.198	-0.027	11.685	-0.014	3.948	1.255	-0.042	19.963	0.000
0.2	15.090	2.582	1.314	-0.047	9.209	-0.009	3.708	1.403	-0.068	16.498	0.012
0.3	15.254	2.425	1.415	-0.068	16.224	0.007	3.137	1.514	-0.088	14.683	0.022
0.4	15.130	2.320	1.437	-0.074	17.610	0.014	2.810	1.520	-0.091	15.457	0.024
0.5	15.176	2.220	1.430	-0.075	16.305	0.016	2.592	1.499	-0.089	15.334	0.025
0.6	15.343	2.143	1.408	-0.073	17.007	0.017	2.443	1.468	-0.086	15.178	0.025
0.8	15.281	2.033	1.369	-0.070	15.913	0.019	2.247	1.406	-0.077	15.259	0.024
1	14.866	1.962	1.323	-0.063	16.862	0.020	2.116	1.358	-0.071	15.006	0.024
1.5	13.983	1.842	1.230	-0.048	15.135	0.016	1.941	1.241	-0.051	14.386	0.019
2	13.098	1.780	1.153	-0.032	15.244	0.009	1.835	1.159	-0.034	14.832	0.011
3	13.008	1.673	1.057	-0.010	10.787	-0.003	1.694	1.059	-0.011	10.747	-0.001
4	12.942	1.606	0.975	0.013	12.265	-0.016	1.605	0.992	0.006	12.836	-0.009
5	12.869	1.530	0.955	0.019	10.807	-0.016	1.535	0.942	0.022	14.024	-0.023

6	12.853	1.481	0.933	0.026	12.285	-0.023	1.465	0.935	0.024	15.102	-0.029
8	12.874	1.397	0.915	0.030	13.876	-0.026	1.375	0.913	0.031	13.884	-0.026
10	12.879	1.335	0.900	0.038	13.037	-0.033	1.308	0.906	0.035	14.332	-0.031
15	12.857	1.245	0.866	0.051	14.817	-0.048	1.228	0.835	0.063	14.194	-0.058

Table 4 Equivalent atomic number (Z_{eq}) and GP exposure (EBF) and energy absorption (EABF) buildup factor coefficients for BG3.

Energy (MeV)	Z_{eq}	EBF					EABF				
		B	**c**	**a**	**X_k**	**d**	**b**	**c**	**a**	**X_k**	**d**
0.015	12.955	1.029	0.394	0.206	15.416	-0.139	1.029	0.366	0.239	14.086	-0.169
0.02	13.061	1.066	0.387	0.217	14.052	-0.120	1.071	0.354	0.237	14.464	-0.127
0.03	13.172	1.215	0.417	0.201	14.904	-0.106	1.218	0.411	0.208	14.120	-0.114
0.04	13.248	1.456	0.492	0.172	14.665	-0.094	1.478	0.483	0.176	14.774	-0.097
0.05	13.300	1.727	0.639	0.110	15.965	-0.056	1.856	0.580	0.139	15.320	-0.080
0.06	13.335	2.088	0.699	0.100	13.719	-0.056	2.348	0.656	0.119	14.335	-0.078
0.08	13.392	2.544	0.890	0.044	13.659	-0.041	3.263	0.884	0.045	14.062	-0.039
0.1	13.412	2.754	1.071	0.000	13.262	-0.023	3.874	1.097	-0.008	13.631	-0.016
0.15	13.495	2.804	1.315	-0.050	16.009	0.000	4.092	1.394	-0.068	14.089	0.014
0.2	13.444	2.723	1.419	-0.067	12.802	0.004	3.685	1.549	-0.094	14.251	0.028
0.3	13.640	2.505	1.483	-0.080	16.655	0.015	3.107	1.601	-0.103	14.383	0.031
0.4	13.502	2.378	1.485	-0.083	16.128	0.017	2.786	1.582	-0.101	14.663	0.030
0.5	13.423	2.272	1.466	-0.082	16.362	0.019	2.592	1.534	-0.095	15.210	0.027
0.6	13.459	2.188	1.437	-0.079	17.798	0.022	2.430	1.510	-0.094	14.893	0.030
0.8	13.459	2.067	1.384	-0.072	15.790	0.021	2.239	1.432	-0.083	14.867	0.028
1	12.900	1.995	1.337	-0.066	15.835	0.022	2.119	1.369	-0.071	15.075	0.026
1.5	12.559	1.860	1.231	-0.048	15.368	0.017	1.940	1.247	-0.052	14.629	0.020
2	11.765	1.789	1.155	-0.033	15.728	0.011	1.837	1.162	-0.036	14.495	0.013
3	11.818	1.676	1.063	-0.013	15.434	-0.002	1.698	1.059	-0.011	14.061	0.000
4	11.745	1.600	0.996	0.005	12.981	-0.009	1.609	0.990	0.007	14.139	-0.010
5	11.720	1.537	0.945	0.022	11.534	-0.021	1.547	0.929	0.026	12.925	-0.024
6	11.725	1.487	0.929	0.026	11.842	-0.021	1.475	0.929	0.025	15.567	-0.028
8	11.724	1.405	0.902	0.034	13.764	-0.028	1.382	0.907	0.032	12.046	-0.023
10	11.704	1.343	0.883	0.042	13.119	-0.033	1.313	0.911	0.031	14.387	-0.026
15	11.710	1.256	0.840	0.059	14.271	-0.053	1.229	0.857	0.052	14.317	-0.046

Table 5 Equivalent atomic number (Z_{eq}) and GP exposure (EBF) and energy absorption (EABF) buildup factor coefficients for BG4.

Energy (MeV)	Z_{eq}	EBF					EABF				
		B	**c**	**a**	**X_k**	**d**	**b**	**c**	**a**	**X_k**	**d**
0.015	14.508	1.020	0.374	0.236	11.996	-0.153	1.020	0.406	0.201	11.599	-0.104
0.02	14.647	1.044	0.430	0.176	15.144	-0.088	1.044	0.416	0.189	14.980	-0.100
0.03	14.781	1.149	0.394	0.214	14.321	-0.115	1.149	0.391	0.218	13.983	-0.122
0.04	14.875	1.323	0.442	0.194	14.418	-0.108	1.331	0.441	0.193	14.654	-0.107
0.05	14.934	1.540	0.524	0.160	14.717	-0.089	1.580	0.530	0.154	15.343	-0.082
0.06	14.984	1.753	0.634	0.117	14.788	-0.063	1.987	0.536	0.168	13.698	-0.087
0.08	15.055	2.190	0.757	0.083	13.051	-0.051	2.754	0.722	0.098	13.499	-0.066
0.1	15.089	2.419	0.933	0.033	13.971	-0.041	3.427	0.916	0.038	13.682	-0.042
0.15	15.168	2.590	1.187	-0.025	11.839	-0.015	3.929	1.239	-0.039	18.772	-0.002
0.2	15.189	2.572	1.309	-0.046	9.407	-0.009	3.705	1.396	-0.066	16.861	0.011
0.3	15.254	2.425	1.415	-0.068	16.224	0.007	3.137	1.514	-0.088	14.683	0.022
0.4	15.287	2.313	1.433	-0.074	18.133	0.014	2.815	1.512	-0.089	15.726	0.023

0.5	15.312	2.217	1.427	-0.075	16.300	0.015	2.593	1.495	-0.088	15.361	0.024
0.6	15.341	2.143	1.408	-0.073	17.005	0.017	2.443	1.468	-0.086	15.177	0.025
0.8	15.280	2.033	1.369	-0.070	15.913	0.019	2.247	1.406	-0.077	15.259	0.024
1	14.864	1.962	1.323	-0.063	16.861	0.020	2.116	1.358	-0.071	15.006	0.024
1.5	13.980	1.842	1.230	-0.048	15.137	0.016	1.941	1.241	-0.051	14.386	0.019
2	13.273	1.778	1.154	-0.032	15.110	0.009	1.836	1.159	-0.034	14.730	0.011
3	13.127	1.672	1.057	-0.010	10.743	-0.003	1.695	1.058	-0.011	10.850	-0.001
4	13.060	1.606	0.976	0.012	12.448	-0.016	1.604	0.992	0.006	12.744	-0.009
5	13.049	1.529	0.958	0.018	10.907	-0.016	1.533	0.945	0.021	14.193	-0.022
6	12.994	1.481	0.933	0.026	12.328	-0.024	1.464	0.936	0.024	15.052	-0.029
8	12.998	1.396	0.917	0.030	13.880	-0.026	1.374	0.913	0.031	14.147	-0.027
10	12.995	1.334	0.902	0.038	13.030	-0.033	1.308	0.904	0.036	14.301	-0.032
15	13.001	1.244	0.869	0.050	14.908	-0.048	1.228	0.833	0.064	14.200	-0.059

Table 6 Equivalent atomic number (Z_{eq}) and GP exposure (EBF) and energy absorption (EABF) buildup factor coefficients for BG5.

Energy (MeV)	Z_{eq}	EBF					EABF				
		B	**c**	**a**	$\mathbf{X_k}$	**d**	**b**	**c**	**a**	$\mathbf{X_k}$	**d**
0.015	12.485	1.033	0.398	0.209	14.409	-0.136	1.033	0.383	0.225	13.721	-0.152
0.02	12.572	1.075	0.407	0.202	14.031	-0.108	1.078	0.381	0.218	14.354	-0.114
0.03	12.665	1.244	0.431	0.195	14.865	-0.103	1.248	0.425	0.201	14.125	-0.109
0.04	12.728	1.516	0.517	0.160	14.883	-0.086	1.541	0.509	0.164	14.957	-0.089
0.05	12.770	1.840	0.659	0.105	15.851	-0.053	1.998	0.582	0.144	14.408	-0.084
0.06	12.805	2.242	0.715	0.098	13.280	-0.058	2.501	0.701	0.103	14.437	-0.073
0.08	12.853	2.684	0.940	0.031	13.091	-0.033	3.453	0.945	0.028	14.144	-0.030
0.1	12.892	2.874	1.122	-0.012	12.908	-0.017	4.019	1.162	-0.023	13.435	-0.007
0.15	12.936	2.887	1.363	-0.059	21.320	0.008	4.138	1.450	-0.078	14.181	0.020
0.2	12.865	2.774	1.466	-0.076	16.886	0.013	3.685	1.598	-0.102	14.099	0.033
0.3	13.288	2.527	1.498	-0.083	16.418	0.016	3.104	1.620	-0.106	14.316	0.033
0.4	13.012	2.402	1.498	-0.085	16.442	0.019	2.791	1.593	-0.103	14.758	0.031
0.5	12.885	2.290	1.477	-0.084	16.364	0.020	2.603	1.536	-0.095	15.356	0.026
0.6	12.871	2.200	1.451	-0.082	16.813	0.023	2.427	1.524	-0.096	14.764	0.032
0.8	13.459	2.067	1.384	-0.072	15.790	0.021	2.239	1.432	-0.083	14.867	0.028
1	12.901	1.995	1.337	-0.066	15.835	0.022	2.119	1.369	-0.071	15.075	0.026
1.5	11.885	1.868	1.233	-0.049	14.596	0.017	1.940	1.249	-0.053	14.485	0.020
2	11.492	1.791	1.155	-0.033	15.275	0.011	1.839	1.160	-0.035	14.584	0.013
3	11.445	1.679	1.060	-0.012	13.212	-0.001	1.701	1.055	-0.010	12.525	0.000
4	11.383	1.603	0.994	0.006	12.923	-0.009	1.611	0.987	0.008	13.671	-0.011
5	11.392	1.537	0.950	0.019	13.174	-0.021	1.545	0.936	0.023	12.811	-0.020
6	11.363	1.490	0.921	0.028	11.615	-0.023	1.477	0.929	0.024	15.765	-0.028
8	11.390	1.406	0.902	0.033	13.658	-0.027	1.385	0.905	0.033	12.152	-0.023
10	11.380	1.345	0.880	0.042	13.151	-0.033	1.318	0.903	0.033	14.180	-0.027
15	11.369	1.259	0.832	0.061	14.308	-0.054	1.227	0.874	0.046	14.508	-0.040

Table 7 Equivalent atomic number (Z_{eq}) and GP exposure (EBF) and energy absorption (EABF) buildup factor coefficients for BG6.

Energy (MeV)	Z_{eq}	EBF					EABF				
		B	**c**	**a**	$\mathbf{X_k}$	**d**	**b**	**c**	**a**	$\mathbf{X_k}$	**d**
0.015	13.468	1.026	0.373	0.233	13.824	-0.158	1.026	0.388	0.216	12.706	-0.126
0.02	13.583	1.058	0.409	0.196	16.079	-0.113	1.060	0.395	0.204	16.258	-0.116
0.03	13.702	1.192	0.403	0.211	14.312	-0.113	1.193	0.401	0.212	14.301	-0.116
0.04	13.782	1.405	0.469	0.183	14.425	-0.103	1.423	0.463	0.185	14.657	-0.103

0.05	13.835	1.660	0.593	0.129	15.315	-0.068	1.718	0.599	0.124	16.497	-0.065
0.06	13.876	1.929	0.701	0.093	15.004	-0.052	2.209	0.613	0.135	13.701	-0.078
0.08	13.942	2.413	0.843	0.057	14.566	-0.050	3.078	0.826	0.062	13.997	-0.048
0.1	13.973	2.633	1.020	0.011	13.633	-0.030	3.719	1.030	0.008	13.764	-0.026
0.15	14.065	2.725	1.268	-0.041	10.476	-0.007	4.037	1.342	-0.059	14.346	0.009
0.2	14.020	2.674	1.374	-0.058	7.747	-0.005	3.679	1.504	-0.087	14.397	0.024
0.3	14.020	2.482	1.468	-0.078	16.937	0.014	3.110	1.581	-0.100	14.444	0.029
0.4	14.216	2.348	1.466	-0.080	16.119	0.016	2.786	1.561	-0.098	14.716	0.029
0.5	14.197	2.246	1.451	-0.079	16.302	0.018	2.574	1.534	-0.096	14.957	0.029
0.6	14.031	2.176	1.424	-0.076	18.598	0.021	2.433	1.496	-0.091	15.008	0.028
0.8	14.032	2.052	1.384	-0.073	15.292	0.021	2.242	1.424	-0.081	15.084	0.027
1	14.022	1.980	1.323	-0.063	15.838	0.018	2.124	1.358	-0.071	14.981	0.024
1.5	12.655	1.859	1.231	-0.048	15.509	0.017	1.940	1.246	-0.052	14.649	0.020
2	12.171	1.786	1.155	-0.033	15.970	0.010	1.834	1.164	-0.036	14.503	0.013
3	12.234	1.674	1.062	-0.012	15.114	-0.002	1.696	1.061	-0.012	13.812	0.000
4	12.166	1.600	0.993	0.006	12.883	-0.010	1.607	0.992	0.006	14.165	-0.009
5	12.183	1.536	0.944	0.023	10.308	-0.020	1.546	0.926	0.027	13.237	-0.026
6	12.135	1.484	0.934	0.024	12.055	-0.020	1.473	0.930	0.025	15.368	-0.029
8	12.157	1.404	0.904	0.033	13.855	-0.028	1.379	0.910	0.032	12.317	-0.024
10	12.135	1.341	0.888	0.041	13.082	-0.033	1.309	0.916	0.030	14.532	-0.026
15	12.153	1.252	0.850	0.056	14.346	-0.051	1.231	0.842	0.059	14.166	-0.053

From all the selected bioactive glass samples, BG4 which has the highest equivalent atomic number possesses minimum values for the EABF and EBF, whereas maximum values are observed for BG5 which has the lowest equivalent atomic number. This is most likely due to that BG4 has the maximum concentration of Ca. On the other hand, the maximum EABF and EBF values shift to higher energies for high Zeq bioactive glass samples, this can be found at 0.2 MeV for BG5 (lowest Zeq) at 10 mfp, whereas the maximum value of EABF and EBF occurs at 0.3 MeV for BG4 (highest Zeq).

Moreover, the EABF values were found in the range 1.03-1606.82, 1.02-1257.98, 1.03-1966.26, 1.02-1257.98, 1.03-2305.65 and 1.03-1666.42 for BG1, BG2, BG3, BG4, BG5 and BG6 bioactive glasses, respectively. Whereas, The EBF values are found in the range 1.03-880.57, 1.02-754.51, 1.03-1077.61, 1.02-754.51,1.03-1234.80 and 1.03-88.02 for BG1, BG2, BG3, BG4, BG5 and BG6 bioactive glass sample respectively.

EABF and EBF variation of the penetration depth of bioactive glasses at determined photon energies of 0.015MeV, 0.15MeV, 1.5MeV and 15MeV is shown in Figs. 5 and 6 respectively. In general, it was found that the values of EABF and EBF of the bioactive glasses increase with penetration depths, and they were lowest for 1mfp and highest for 10mfp penetration depths due to multiple scattering events at large penetration depths.

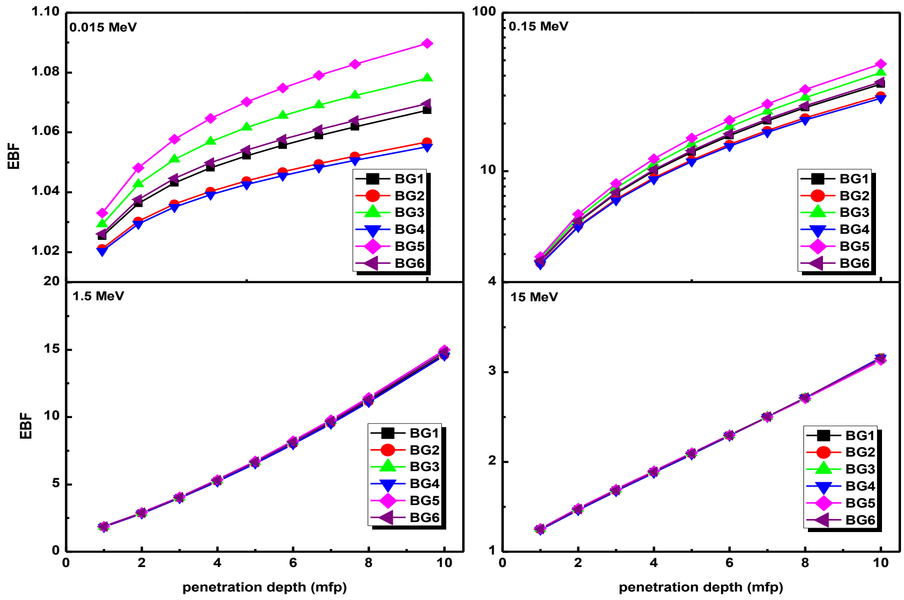

Fig. 5. Theexposurebuildupfactorfor bioactive glasses upto 10mfpat0.015,0.15,1.5and15MeV.

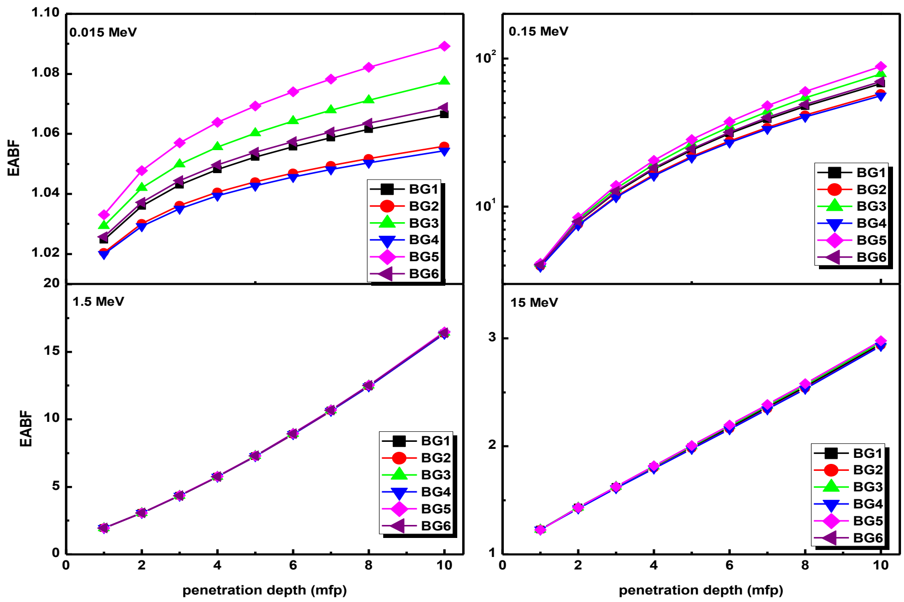

Fig. 6. The energy absorption buildup factors for bioactive glasses upto 10mfpat0.015,0.15,1.5and15MeV.

At photon energy 0.015 MeV, a significant variation is found in the EABF and EBF for the selected bioactive glasses. For the glasses with lower Zeq (BG5, BG3, and BG6) the EABF and EBF values are large, while the glasses with higher Zeq (BG4) posses the lowest value of EABF and EBF. This variation in EABF and EBF decreases as the photon energy approaches 0.15 MeV.

At incident photon energies of 1.5 MeV and 15.0 MeV, it was found that EABF and EBF values become nearly independent of chemical composition and the magnitude of the EABF and EBF has been reduced, however, the number of multiplicity of Compton scattering has been increased so much that it cannot even recognize the interacting material same as mentioned by Sayyed and his colleagues [23]. At very high incident photon energies, beyond 3MeV, it has been observed that BG4 (maximum Zeq) possesses maximum values of EABF and EBF, while minimum values are observed for BG5 (minimum Zeq). This reversal trend can be explained on the basis that at this incident photon energy was dominated by pair production photon interaction process.

5. Conclusions

The bioactive glass used as implant materials in the human body to repair diseased or damaged tissue. In this work, the mass attenuation coefficient (μ/ρ) and KERMA relative to air (Ka) of bioactive glasses in the energy range of 1keV to 10MeV was determined. The values of μ/ρ and Ka were found obviously depend on the incident photon energy and chemical composition.

Furthermore, gamma ray energy absorption buildup factors (EABF) and exposure buildup factors values (EBF) were calculated by Geometric Progression method (GP) for incident photon energy 15keV to 15MeV up to penetration depths of 10 mfp. Among the selected glasses, BG4 possesses minimum values for the EABF and EBF, whereas maximum values are observed for BG5. The obtained results in this work will be useful in medical and biological applications, diagnostics and radiation therapy.

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