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CHEMICAL COMPOSITION DEPENDENCE OF BUILDUP FACTORS FOR SOME BIOLOGICAL MATERIALS

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Abstract

Buildup factors for some biological materials such as myristic acid, oleic acid, bone, muscle, tyrosine and cysteine have been computed using the five parameter geometric progression (GP) fitting method in the energy range of 0.015- 15.0 MeV, up to the penetration of 40 mean free paths (mfp). The variation of exposure and energy absorption buildup factors for all the selected biological samples with incident photon energy at the fixed penetration depths has been studied, mainly emphasizing on chemical composition (equivalent atomic number) of the selected samples. This change results from the dominance of different interaction processes in different energy regions and the chemical composition of different materials.

Keywords: Gamma ray build-up factor, Exposure buildup factor, Energy absorption buildup factor and Equivalent atomic number.

Keywords: Gamma ray build-up factor, Exposure buildup factor (EBF), Energy absorption buildup factor (EABF), Equivalent atomic number and effective atomic number.

1. INTRODUCTION

In the medical and biological context, gamma ray buildup factor is of importance in the distribution of photon flux and in the calculation of radiation dose received by the biological molecules in addition to the importance of the knowledge on other photon interaction parameters such as effective atomic numbers and mass attenuation coefficients in biological materials. Since radiation is hazardous for living organisms as well as materials, the needed precaution must be taken by shielding the radiation sources. However, there is an undesired situation faced by the radiation physicists, oncologists and engineers that while designing the shield or estimating the absorbed dose, secondary radiation can occur due to buildup of photons that arise from the collided part of the incident beam. For this reason it is of importance to determine the buildup factors to make correction for effective exposure and energy deposition in different shielding and biological media. There are two types of buildup factors: (a) exposure buildup factor in which the quantity of interest is the exposure and detector response function is that of absorption in air (Harima 1993). (b) Energy absorption buildup factor in which quantity of interest is the absorbed or deposited energy in the interacting material and the detector response function is that of absorption in the interacting material.

The buildup factor measures the degree of violation of the Lambert-Beer law ($I = I_0 e^{-\mu x}$), where B is known as buildup factor (Singh et.al., 2008), its classification into two categories (EBF and EABF) and different methods are available to calculate the buildup factors such as the G-P

fitting method (Harima et al., 1986), iterative method (Suteau and Chiron 2005), Monte Carlo method (Sardari et al., 2009) and invariant embedding method (Sakamoto and Tanaka 1988; Shimizu, 2002; Shimizu et al., 2004); Mann K.S and Sidhu G.S (2012a) about silicates; (Mann et. al 2012) buildup factor of building materials and (Kumar V et al. 2012) studied about low-Z alkali minerals as gamma ray shields. Chaudhari Laxman M. (2013) computed the linear and mass absorption coefficients of various leaves of Asoka plant by using beta sources Cs and Tl. The linear and mass absorption coefficient values are useful for quantitative evaluation of interaction of radiations with leaves of plants.

Ishar et al. (2014) computed interaction parameters in dana's Minerals. In present work, the exposure and energy absorption buildup factors have been computed for some selected biological samples in the energy range of 0.015 - 15.0 MeV, up to penetration depth of 40 mfp. The emphasis has been focused on the dependence of buildup factor on the chemical composition or equivalent atomic number (Z_{eq}) of the selected biological samples.

The Chemical Composition of bone and muscle taken from research paper "Effective atomic numbers for low-energy total photon interactions in human tissues by N.C. Yang, P.K. Leichner and W.G. Hawkins (1987) pp 759-766. The Chemical Composition of Myristic Acid and Oleic Acid taken from research paper "On the effective atomic number and electron density: A comprehensive set of formulas for all types of materials and energies above 1 keV by S.R. Manohara, S.M. Hanagodimath, K.S. Thind and L. Greward B 266 (2008) 3906-3912 and the Chemical Composition Tyrosine and Cysteine taken from research paper " Effective atomic numbers and electron densities of amino acids containing H, C, N and O by Pravina P. Pawar and Govind K. Bichile 2011, 2 (4) ; page 94-103. The chemical composition of the selected samples has been given in table 1.

Table 1. Chemical composition by weight of different biological samples.

Biological materials	**Chemical composition (%age by weight)**
Myristic Acid	H: 12.358, C: 73.630,O: 14.012
Oleic acid	H: 12.132, C:76.539, O: 11.329
Bone	H: 5.6, C: 9.3, N: 3.3, O:39.4, Na: 0.4, Mg: 0.4, P: 13.4, K: 0.2, Ca: 28
Muscle	H: 10.29, C: 9.89, N: 3.196, O: 75.624, Na: 0.1, P: 0.2, S: 0.3, Cl: 0.1, K: 0.3
Tyrosine	H: 6.120, C: 59.66, N: 7.73, O: 26.49
Cysteine	H: 5.033, C: 29.989, N: 11.658, O: 26.632, S: 26.688

2. COMPUTATIONAL WORK

The computational work of buildup factor has been divided into three parts. The first part concern with the computation of equivalent atomic number (Z_{eq}) for the selected biological samples. The second part deals with the computation of G.P. fitting parameters and finally in the third part, buildup factor values have been computed. The results so obtained have been shown in the tabular form (Table 2.) for Z_{eq} the selected biological samples.

2.1 Computation of equivalent atomic number

Firstly the values of Compton partial attenuation coefficient (μ_{comp}) and total attenuation coefficients $(\mu)_{tot}$ in cm^2/g were

obtained for elements from Z = 1 to 25 for the selected samples in the energy of 0.015–15.0 MeV, using the state-of-the-art and convenient computer program XCOM and WinXCom. Further, by using a simple computer program, the ratio R(μ_{comp}/μ_{tot}) was obtained for selected samples. Then the value of equivalent atomic number (Z_{eq}) for these samples was calculated by matching the ratio R (μ_{comp}/μ_{tot}) of particular sample at a given energy with corresponding ratios of elements at the same energy. For the case the ratio lies in between the two ratios of known elements. The value of Z_{eq} was interpolated by using the following formula of interpolation (Harima, 1993) given in the following equation.

$$Z_{eq} = \frac{Z_1(\log R_2 - \log R) + Z_2(\log R - \log R_1)}{\log R_2 - \log R_1} \quad (1)$$

WhereZ_1 and Z_2 are the atomic numbers of elements corresponding to the (μ_{comp}/μ_{total}) ratios, R_1 and R_2, respectively; and R (μ_{comp}/μ_{total}) is the ratio for the selected biological samples at a particular energy which lies between ratios R_1 and R_2.

samples.

Table 2. Equivalent atomic numbers of different Biological samples in the energy range of 0.015 - 15.0 MeV.

Energy (MeV)	Equivalent atomic number (Z_{eq})					
	Myristic acid	**Oleic acid**	**Bone**	**Muscle**	**Tyrosine**	**Cysteine**
0.015	5.93	5.88	13.72	7.50	6.52	10.75
0.020	5.97	5.90	13.92	7.55	6.54	10.87
0.030	5.97	5.88	14.14	7.60	6.51	11.00
0.040	5.99	5.92	14.25	7.61	6.53	11.10
0.050	6.06	5.93	14.34	7.60	6.56	11.19
0.060	6.06	5.83	14.44	7.63	6.38	11.26
0.080	6.34	5.74	14.49	7.78	6.92	11.32
0.100	6.50	6.72	14.61	7.71	6.81	11.42
0.150	6.50	6.50	14.68	7.50	6.50	10.77
0.200	6.50	6.50	14.85	7.50	6.50	10.50
0.300	6.50	6.50	14.50	7.50	6.50	10.50
0.400	6.50	6.50	14.50	7.50	6.50	10.50
0.500	6.50	6.50	14.50	7.50	6.50	10.50
0.600	6.50	6.50	14.50	7.50	6.50	10.50
0.800	6.50	6.50	14.50	7.50	6.50	10.50
1.000	6.50	6.50	14.50	7.50	6.50	10.50
1.500	6.50	6.50	14.50	7.50	6.50	10.50
2.000	6.50	6.50	12.45	7.50	6.50	8.56
3.000	5.40	5.41	10.71	6.48	6.24	8.51
4.000	5.12	5.18	11.14	6.47	5.72	8.59
5.000	5.09	4.83	11.13	6.57	5.95	8.98
6.000	5.16	5.18	11.16	6.75	6.12	8.64
8.000	5.23	5.26	11.07	6.70	5.99	8.62
10.00	4.95	4.98	10.95	6.54	6.09	8.49
15.00	5.01	4.92	11.10	6.47	5.95	8.49

2.2 Computation of G.P. fitting parameters

American National Standard has provided the energy exposure G.P. fitting parameters of 23 elements (Be, B, C, N, O, Na, Mg, Al,Si, P, S, Ar, K, Ca, Fe, Cu, Mo, Sn, La, Gd, W, Pb and U), one compound(water) and two mixtures (air and concrete) in the energy range of 0.015–15.0 MeV and up to a penetration depth of 40 mfp (ANSI/ANS-6.4.3-1991). Using the interpolation formula, five G.P. fitting parameters (b, c, a, X_k and d) for selected samples were computed at the different incident photon energies using equivalent atomic number (Z_{eq}), in the chosen energy range (0.015–15.0 MeV) up to penetration depth of 40 mfp. The formula used for the purpose of interpolation (Sidhu et al., 1999 a, b) is as follows:

$$P = \frac{P_1(\log Z_2 - \log Z_{eq}) + P_2(\log Z_{eq} - \log Z_1)}{\log Z_2 - \log Z_1} \quad (2)$$

Here P_1 and P_2 are the values of G.P. fitting parameters corresponding to the atomic numbers Z_1 and Z_2 respectively at a fixed energy, whereas Z is the equivalent atomic number of the selected sample at the same energy. Z_1 and Z_2 are the elemental atomic numbers between which the equivalent atomic number Z of the chosen samples lies. The computed G.P. fitting parameters of oleic acid and bone are listed in Tables 3 and 4 respectively.

Table 3. Exposure and energy absorption G-P fitting parameters for sample oleic acid.

G-P fitting coefficients for EBF						G-P fitting coefficients for EABF				
Energy(MeV)	*b*	*c*	*a*	X_K	*d*	*b*	*c*	*a*	X_K	*d*
1.50E- 02	1.4239	0.5550	0.1403	14.3887	-0.0689	1.4372	0.5428	0.1468	14.4865	-0.0743
2.00E- 02	1.9442	0.7523	0.0738	16.3170	-0.0376	1.9710	0.7581	0.0713	16.3384	-0.0352
3.00E- 02	3.6360	1.2069	-0.0365	12.9947	0.0130	3.8298	1.2029	-0.0357	12.8099	0.0123
4.00E- 02	5.3766	1.7803	-0.1329	13.9596	0.0586	5.1021	1.7693	-0.1309	14.1163	0.0570
5.00E- 02	6.7838	2.1393	-0.1730	14.3474	0.0749	5.1016	2.0901	-0.1663	14.4954	0.0700
6.00E- 02	7.4174	2.4687	-0.2054	14.5042	0.0909	5.4112	2.3448	-0.1909	14.6874	0.0803
8.00E- 02	7.0766	2.8037	-0.2352	14.4918	0.1026	4.7923	2.5593	-0.2092	14.8524	0.0839
1.00E- 01	5.3886	2.4469	-0.2037	13.3926	0.0884	4.5667	2.3274	-0.1899	14.5859	0.0787
1.50E- 01	4.1676	2.6515	-0.2268	14.1244	0.1003	3.6404	2.3913	-0.1967	14.6744	0.0779
2.00E- 01	3.5657	2.5474	-0.2200	14.1661	0.0972	3.2727	2.2767	-0.1872	14.7856	0.0759
3.00E- 01	3.0509	2.2723	-0.1949	14.2283	0.0846	2.8198	2.0911	-0.1714	14.5706	0.0680
4.00E- 01	2.7687	2.0822	-0.1769	13.7712	0.0745	2.6243	1.9110	-0.1520	14.5129	0.0616
5.00E- 01	2.5952	1.9196	-0.1580	14.1588	0.0700	2.4591	1.7927	-0.1380	15.0478	0.0585
6.00E- 01	2.4719	1.7918	-0.1422	13.8648	0.0590	2.3803	1.6718	-0.1216	14.5958	0.0479
8.00E- 01	2.2751	1.6334	-0.1221	13.9194	0.0560	2.2001	1.5531	-0.1069	14.1471	0.0447
1.00E+00	2.1562	1.5077	-0.1027	13.8787	0.0477	2.0979	1.4444	-0.0894	14.4700	0.0380
1.50E+00	1.9887	1.2897	-0.0633	14.2716	0.0287	1.9358	1.2760	-0.0600	14.3367	0.0263
2.00E+00	1.8772	1.1837	-0.0419	13.9692	0.0190	1.8388	1.1717	-0.0386	14.2288	0.0158
3.00E+00	1.7705	1.0642	-0.0162	12.4061	0.0086	1.7150	1.0522	-0.0121	13.6174	0.0042
4.00E+00	1.6794	0.9792	0.0057	18.3923	-0.0050	1.6294	0.9866	0.0039	14.9404	-0.0033
5.00E+00	1.6054	0.9328	0.0178	15.2961	-0.0097	1.5716	0.9385	0.0167	13.8514	-0.0096
6.00E+00	1.5379	0.9048	0.0260	14.8108	-0.0143	1.5238	0.9024	0.0276	13.0101	-0.0152
8.00E+00	1.4450	0.8716	0.0358	14.9871	-0.0243	1.4451	0.8639	0.0380	11.4219	-0.0210
1.00E+01	1.3838	0.8518	0.0414	13.4416	-0.0183	1.3892	0.88558	0.0430	14.4946	-0.0208
1.50E+01	1.2874	0.8280	0.0486	13.8815	-0.0243	1.2963	0.8329	0.0473	14.0179	-0.0264

Table IV. Exposure and energy absorption G-P fitting parameters for bone.

G-P fitting coefficients for EBF						G-P fitting coefficients for EABF				
Energy(MeV)	*b*	*c*	*a*	X_K X_K	*d* *d*	*b*	*c*	*a*		
1.50E- 02	2.0246	0.3613	0.2467	12.9423	-0.1681	1.0239	0.4011	0.2036	11.9669	-0.1028
2.00E- 02	1.0522	0.4228	0.1822	17.3438	-0.1088	1.0526	0.4200	0.1838	17.3779	-0.1094
3.00E- 02	1.1735	0.3949	0.2156	14.0506	-0.1161	1.1744	0.3943	0.2156	14.3236	-0.1178
4.00E- 02	1.3638	0.4546	0.1898	14.3557	-0.1070	1.3805	0.4509	0.1903	14.6228	-0.1054
5.00E- 02	1.6028	0.5585	0.1444	14.9704	-0.0780	1.6408	0.5765	0.1319	16.2900	-0.0685
6.00E- 02	1.8299	0.6711	0.1032	15.0613	-0.0569	2.0910	0.5731	0.1520	13.6228	-0.0822
8.00E- 02	2.3023	0.7976	0.0710	13.8024	-0.0510	2.9134	0.7731	0.0800	13.7556	-0.0571
1.00E- 01	2.5077	0.9698	0.0237	13.9096	-0.0362	3.5513	0.9633	0.0257	13.7205	-0.0353
1.50E- 01	2.6491	1.2214	-0.0317	11.2768	-0.0114	3.9784	1.2841	-0.0476	18.1059	0.0031
2.00E- 01	2.6025	1.3272	-0.0495	8.8392	-0.0083	3.7062	1.4240	-0.0716	15.9063	0.0141
3.00E- 01	2.4566	1.4507	-0.0749	18.0497	0.0130	3.1121	1.5545	-0.0954	14.3025	0.0261
4.00E- 01	2.3397	1.4562	-0.0779	16.5066	0.0150	2.7932	1.5486	-0.0959	14.9057	0.0275
5.00E- 01	2.2378	1.4438	-0.0780	16.3051	0.0169	2.5802	1.5222	-0.0934	15.0887	0.0277
6.00E- 01	2.1617	1.4199	-0.0755	17.5358	0.0197	2.4381	1.4858	-0.0890	14.9744	0.0270
8.00E- 01	2.0438	1.3799	-0.0720	15.4631	0.0208	2.2435	1.4169	-0.0795	15.1461	0.0254
1.00E+00	1.9693	1.3230	-0.0630	16.4254	0.0194	2.1194	1.3580	-0.0710	14.9953	0.0242
1.50E+00	1.8379	1.2280	-0.0475	15.2421	0.0158	1.9420	1.2374	-0.0500	14.6903	0.0177
2.00E+00	1.7842	1.1541	-0.0325	15.7467	0.0100	1.8345	1.1627	-0.0351	14.6362	0.0119
3.00E+00	1.6863	1.0557	0.0110	10.6722	0.0001	1.7063	1.0502	-0.0092	10.9429	-0.0009
4.00E+00	1.6048	0.9927	0.0059	12.8833	-0.0089	1.6130	0.9843	0.0086	13.3490	-0.0116
5.00E+00	1.5363	0.9540	0.0171	14.5208	-0.0206	1.5429	0.9428	0.0204	12.7173	-0.0167
6.00E+00	1.4923	0.9173	0.0298	11.4846	-0.0238	1.4782	0.9290	0.0242	15.8787	-0.0273
8.00E+00	1.4059	0.9020	0.0331	13.5533	-0.0262	1.3874	0.9034	0.0329	12.2567	-0.0233
1.00E+01	1.3472	0.8759	0.0429	13.2014	-0.0334	1.3245	0.8936	0.0361	13.9296	-0.0286
1.50E+01	1.2620	0.8255	0.0633	14.3386	-0.0557	1.2256	0.8870	0.0401	14.6618	-0.0347

2.3 Computation of exposure buildup factors

The computed G.P. fitting parameters were then used to compute the exposure buildup factors for the selected samples at some standard incident photon energies up to a penetration depth of 40 mean free paths, with the help of G.P. fitting formula, as given by following equations (Harima et al., 1986).

$$B(E,x) = 1 + \frac{(b-1)(K^x - 1)}{K - 1} \quad \text{for} \quad K \neq 1 \qquad (3)$$

$$B(E,x) = 1 + (b-1) \quad \text{for} \quad K = 1 \qquad (4)$$

Where

$$K(E,x) = cx^a + d\,\frac{\tanh(x/X_k - 2) - \tanh(-2)}{1 - \tanh(-2)}, \quad x \leq 40 mfp \qquad (5)$$

where a, b, c, d and X_k are the G-P fitting parameters and x is source to detector distance in the medium (mfp). The parameter K (E, x) represents photon dose multiplication.

3. RESULTS AND DISCUSSION

The results of the present investigations are discussed in terms of exposure and energy absorption build-up factor as a function of incident photon energy.

3.1 Dependence of shielding effectiveness on mass attenuation coefficient

Figure1. Show the results of mass attenuation coefficients for photoelectric process $\mu_{m(photo)}$ of all the selected low-Z biological samples against the incident photon energy. This figure clearly shows the most significant variation in μ_m due to chemical composition of the selected samples.

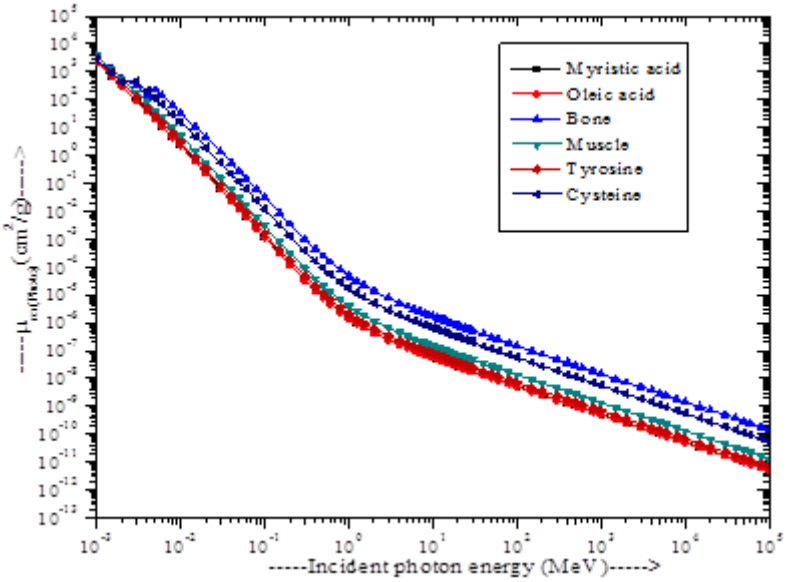

Figure 1. Total mass attenuation coefficient of different types of biological materials as a function of incident photon energy.

These results of $\mu_{m(photo)}$ explain the variation of $\mu_{m(total)}$ with chemical composition in the low energy region because in the low energy region photoelectric effect is predominant. The variation in $\mu_{m(total)}$ are interpreted as being due to the Z-dependence of the partial interaction processes, since the cross-section for photoelectric absorption is proportional to Z^{4-5}. There is a sudden jump in $\mu_{m(photo)}$ at about 2 keV for bone and cysteine which contains larger percentage of comparatively heavy elements like Ca (Z= 20), K (Z=19) ,Mg (Z=15) and S (Z= 16) and resulting larger Z_{eq}. It is also observed that the materials which contain comparatively larger percentages of heavier elements have relatively larger value of $\mu_{m(photo)}$.

3.2 Exposure build-up factor as a function of incident photon energy

Figures 2(a-d) show the variation of exposure and energy absorption build-up factor with incident photon energy at a fixed penetration depths of 1, 5, 15, 25, 35 and 40 mfp for myristic acid and bone. The build-up factors for oleic acid, muscle, tyrosine and cysteine show similar trends, therefore graphical representation is not shown.

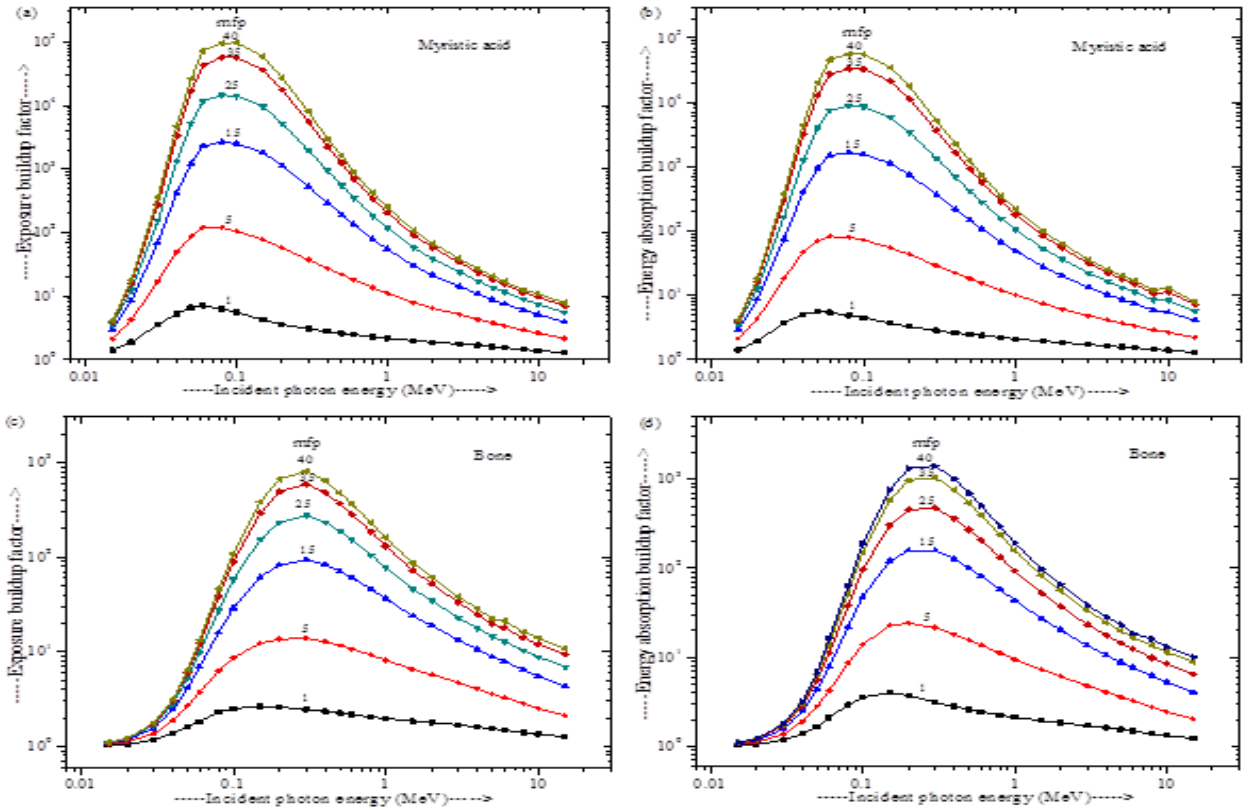

Figure 2. (a- d) Variation of exposure and energy absorption buildup factor for myristic acid and bone.

It is observed that incident photon energies less than E_{pe}, the exposure buildup factor values are relatively lower as compared to that of neighbouring higher energies for all the selected penetration depths. Where E_{pe} is the value of energy at which photoelectric interaction coefficient matches the Compton interaction coefficient for a given biological materials. The low value of buildup factor is due to predominance of photoelectric effect in this energy region, which results in the fast removal of low energy photons thereby not allowing these photons to buildup in the medium. The Compton effect is most dominant interaction process in the energy region of $E_{pe}< E <E_{pp}$(where E_{pp} is the energy value at which the pair production interaction cross section matches the Compton interaction cross section for a particular biological materials.

It has been observed that in the energy region 0.07- 0.9 MeV, the exposure buildup factor values are very high due to the dominance of Compton scattering, which only helps in the degradation of photon energy and not for removal of photon completely, which results in multiplication of photons and leads to higher value of buildup factor. It is also observed that within the energy range 0.05- 0.2 MeV, the exposure buildup factor value is very high because of exclusive dominance of Compton effect. This results in a broad peak around a particular value of incident photon energy, E_{peak}. Further it is also observed that for energies greater than 2.0 MeV, the dominance of pair production phenomenon over the Compton effect increases, resulting in lowering of the build-up factor value at these energies for a given materials.

3. 3 Variation of the build up factors, EBF and EABF, with penetration depths

The calculated EBF and EABF values have been plotted as a function of penetration depth for the selected materials. These are shown in figs. 3(a-h) for some selected photon energies in the energy range 0.015-15.0 MeV. It is can be seen from these figures that, in general, at a particular energy the buildup factor increases with increase in penetration depth for all materials, except at 0.015 MeV. The buildup factor is almost constant (≈ unity) for all penetration depths at 0.015 MeV. At higher energies, the buildup factor increases with increase of penetration depth for all materials. This is because more multiple-scattered photons are generated at large penetration depths thereby increasing the buildup factor.

From Figure 3(f). it is also observed that the energy absorption buildup factor values are practically the same for different selected biological samples at the energy value of 1.5 MeV. Thus, the buildup factor values become almost independent of the chemical composition of the given materials at this energy region, where compton scattering process dominate. From Figure 3 (g-h), it is further noted that at penetration depth greater than 15 mfp, the trend of dependence of exposure and energy absorption buildup factor on Z_{eq} has also been reversed at the incident photon energy of 15.0 MeV.

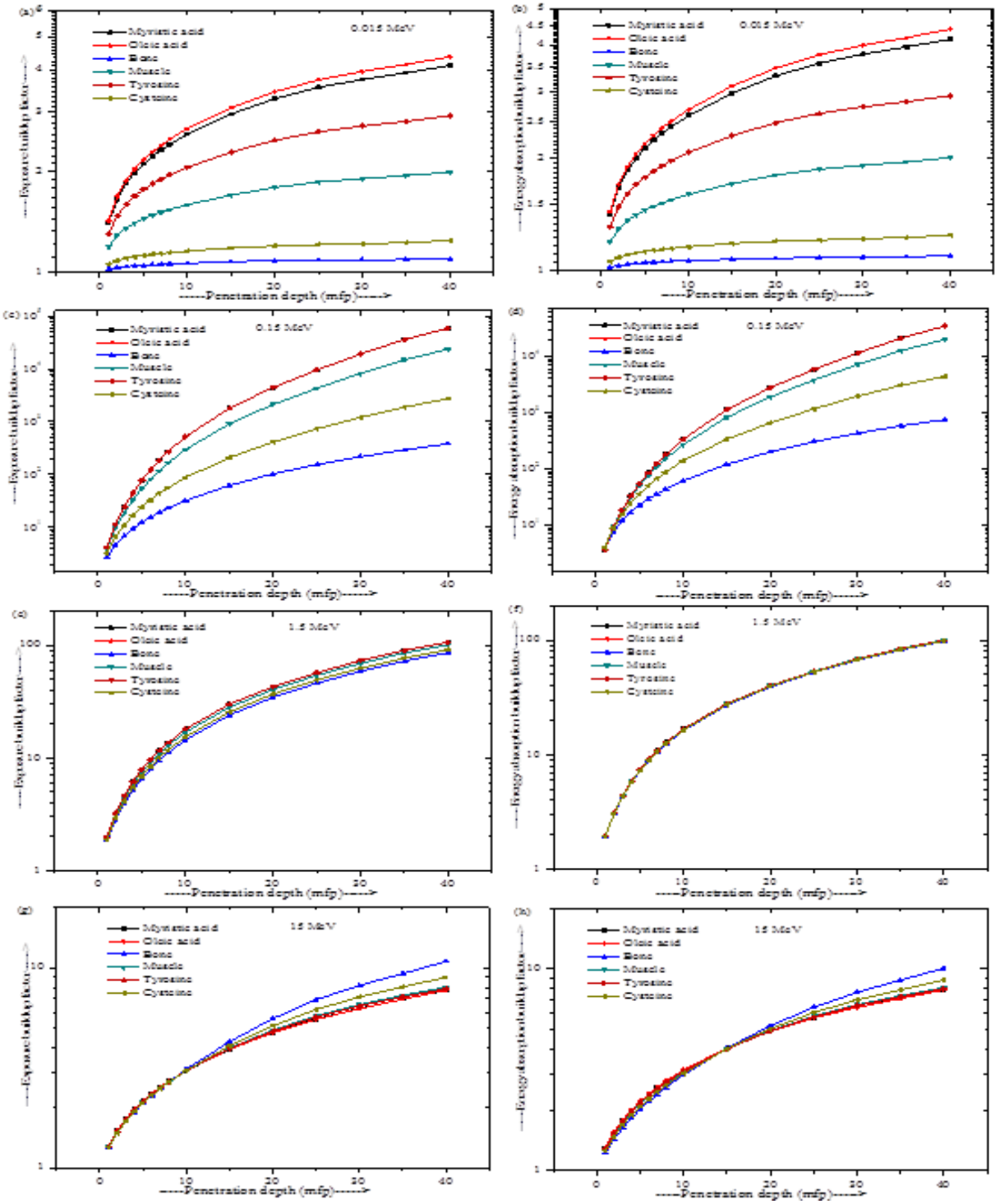

Figure 3. The EBF and EABF values for all chosen minerals up to penetration depth of 40 mfp; (a)-(b) at 0.015 MeV, (c)-(d) at 0.15 MeV, (e)-(f) at 1.5 MeV and (g)-(h) at 15MeV.

4. COMPARISON OF EXPOSURE AND ENERGY ABSORPTION BUILDUP FACTORS

The values of energy absorption buildup factor (EABF) and exposure buildup (EBF) show similar variations with respect to the photon energy, penetration depth and chemical composition but significant differences have also been observed. The maximum differences exist in intermediate energy region where compton scattering is the main photon interaction process, thus leading to large difference between exposure and energy absorption buildup factor. The values of exposure buildup factor are comparatively larger than energy absorption buildup for the samples having low Z_{eq} (myristic acid). On the other hand, for the sample of high Z_{eq} (bone) when compared to air, the absorption inside the medium is much more than the absorption in air. From figs. 3 (a, b) it can be seen that, the percentage difference between energy absorption and exposure buildup factor is high in the intermediate energy region due to the high value of scattered photons.

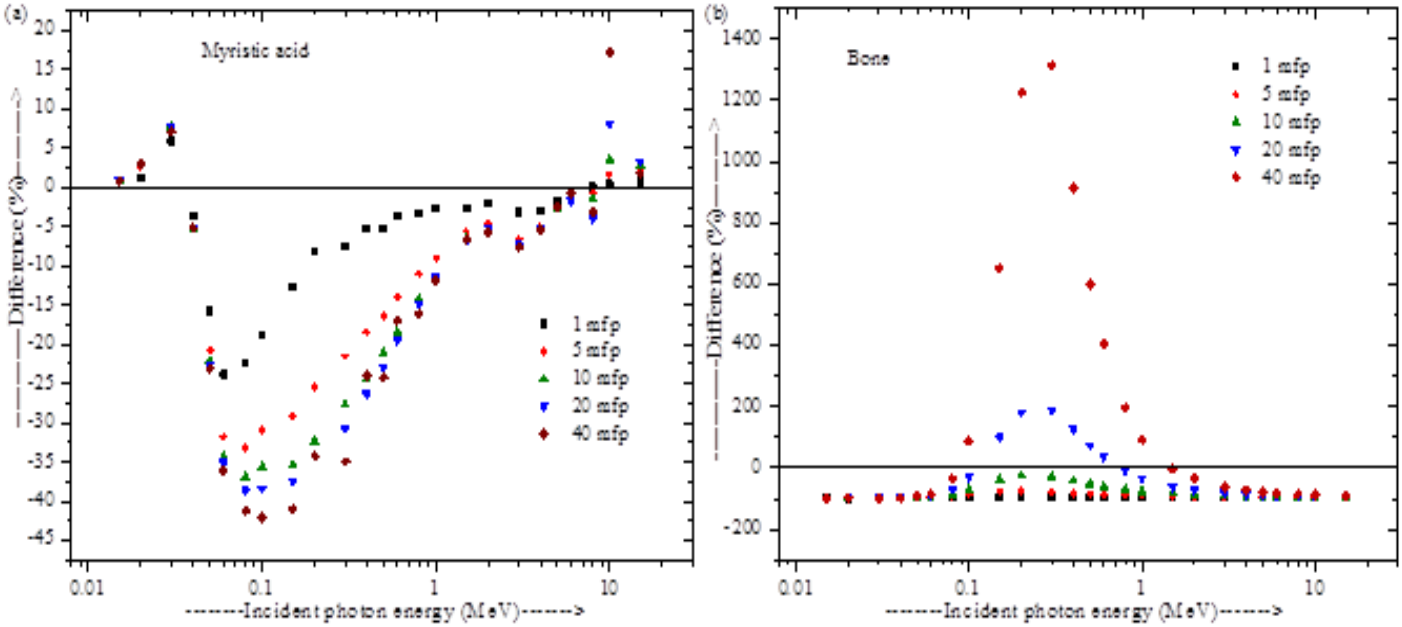

Figure 3. The variation of percentage (%) difference between EBF and EABF for energy range 0.015-15MeV up to 40mfp: (a) for myristic acid and (b) for bone

4. CONCLUSIONS

The chemical composition (equivalent atomic number) plays an important role in the interaction of radiation with the selected biological samples. The exposure build-up factor dependence has been briefly discussed and following conclusion was drawn:

- Below a certain incident photon energy (about 3MeV), for any penetration depths up to 40 mfp, the exposure build-up factor decreases with increase in equivalent atomic number of biological.
- However, above that incident photon energy (3 MeV), variation of the exposure build-up factor with chemical composition also depends upon the penetration depths of the selected tissues.
- The computed data G.P. fitting parameters and energy absorption buildup factors for selected four low-Z shielding materials (25 energies and 40 penetration depths) may be useful in the future study of variety of shielding configurations.

The dosimetric and biological equivalent properties of the present selected samples are very useful in clinical applications such as radiological examinations and therapeutic under radiation conditions where the effective energy of the

photon attenuation field is difficult to assess. Also, knowledge on radiation interaction with matter is also of importance for researchers working in radiological laboratories, reactors and nuclear power plants to take the proper precautions to avoid radiation hazards.

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