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A Study of Energy Absorption and Exposure Buildup Factors in Medicinal Samples

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γ-Ray energy absorption and exposure buildup factors were computed using the five-parameter geometric progression (G-P) fitting formula for 11 vitamins in the energy range 0.015-15 MeV and for penetration depths up to 40 mfp (mean free path). The generated energy absorption (EABF) and exposure (EBF) buildup factors of vitamins have been studied as a function of penetration depth and incident photon energy. The significant variations in EABF and EBF for vitamins have been observed at the intermediate energy region. It has been concluded that the buildup of photons is less in cobalamin (B12) and is more in β-carotene (vitamin A) compared with other vitamins. Also buildup factors of cobalamin and ascorbic acid, antioxidant vitamins, which have radio protective effects, are minimum. Buildup factors investigated in the present work could be useful in radiation dosimetry and therapy.

Keywords: γ-Ray buildup factor, Energy absorption, Exposure, Vitamins, Radio protective.

INTRODUCTION

People are exposed to some amount of radiation each day. In addition to the widely feared nuclear radiation, there are many other forms, including thermal radiation, UV radiation and electromagnetic radiation, which come from X-rays, visible light or radio waves.

Today, radiation is widely used to treat cancer. More than half of all people with cancer get radiation as at least part of their cancer treatment. Radiation therapy may be curative in a number of types of cancer if they are localized to one area of the body. Radiation works by damaging the genes (DNA) in cells. Genes control how cells grow and divide. When radiation damages the genes of cancer cells, they can't grow and divide any more. Over time, the cells die. This means radiation can be used to kill cancer cells and shrink tumors. But there are a number of side effects of radiation, including fatigue, skin burns, hair loss, decreased appetite and decreased blood counts. Even though radiation therapy destroys cancerous tissues, it can also damage healthy tissues. The negative effects of radiation therapy can be reduced some vitamins.

Vitamin A has been proved to speed up your body's recovery process after radiation damage. This nutrient has also been confirmed to offset the toxic effects of partial or full body γ-radiation injury.

Vitamin A is powerful antioxidant that can help aid in the healing of damaged tissue as the result of radiation therapy. The antioxidant properties of vitamin A can help prevent free radicals from binding to our healing tissues. As a result, vitamin A can also help to increase the production of collagen. Increased collagen levels can help to repair damaged tissues and decrease your healing time.

Vitamin E is especially effective in reducing radiation injury from exposure to X-rays [1]. Vitamin E is a natural component of cell membranes and is the strongest antioxidant of the tocopherols. It is also found to be helpful in protection from cesium-137 radiation, which is commonly used in nuclear reactors. This nutrient can prevent the chromosomal changes that usually follow a radiation attack on the cells.

Vitamin E also helps prevent the destruction of vitamin A and fatty acids by massive doses of X-rays. If large doses of C, B and E are taken before exposure, the terrible symptoms of radiation sickness can be reduced or eliminated to a large degree.

Vitamin E is a vitamin that is stored in the fat cells of our body. With antioxidant and ant-inflammatory properties, vitamin E can be beneficial in recovery following radiation therapy. Vitamin E can help prevent free radical damage and moisturize our skin. Skin problems are also commonly associated with radiation therapy. Vitamin E can also help improve blood flow to your tissues, reduce the appearance of scarring, decrease inflammation and help damaged tissues to heal.

Vitamin D is one of the most studied supplements for cancer prevention and treatment right now.

Vitamin B-complex with many B vitamins, especially pantothenic acid, help to decrease the effects of radiation. One of its many functions is that they normalize the red and white blood cell count because the destruction of white blood cells by radiation can last for extended periods of time. Vitamin B12 (cobalamin) plays a protective role when administered prior to irradiation [2]. Cobalamins are intracellular antioxidants *in vitro* [3].

Vitamin C plays an important role in helping tissue to repair itself and play a role in collagen synthesis. Collagen is a protein used to form connective tissue as well as skin and blood vessels. Collagen also helps to form scar tissue including after surgeries or radiation therapy. Vitamin C helps capillaries to form after trauma has occurred to the tissues of your body. Vitamin C also serves as an antioxidant that can help protect your tissues from free radical and environmental damage as they heal.

The knowledge of buildup factors is important in radiation dosimetry and therapy. For example, when evaluating the energy deposition in a tissue phantom exposed to γ-rays, the maximum radiation dose may not be at the surface but somewhere inside, due to the buildup of photons [4]. There are two types of buildup factor: a) the energy absorption buildup factor in which the 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, b) the exposure buildup factor is the buildup factor in which the quantity of interest is the exposure and the detector response function is that of absorption in air [5]. There are different available methods to calculate the buildup factor such as geometric progression fitting method [6]. Several authors have provided different build-up factor data for extensive utilization of design in radiation shields and for other purposes [7]. American National Standards ANSI/ANS 6.4.3 has presented the buildup factor data for 23 elements, one compound and two mixtures (*i.e.* air and water) and concrete at energies in the range 0.015-15 MeV up to penetration depths of 40 mean free path by using the geometric progression method.

Many papers were reported on the buildup factor studies in some biological materials available in the literature [4,8]. But there are almost no studies for buildup factors in vitamins. At this point it could be useful that investigate X and/or γ-radiation interaction of these vitamins for radiotherapy dose limits and dose calculations. In the present paper, we report the energy absorption and exposure buildup factors by using the geometric progression fitting method for some vitamins in the energy region 0.015-15 MeV up to penetration depths of 40 mfp. The effect of some parameters such as photon energy and penetration depth on both the two buildup factors, generated energy absorption (EABF) and exposure (EBF), have been investigated. Also, the comparison of EABF and EBF has been made and significant variations were noted.

CALCULATION METHODS

The geometric progression fitting parameters were obtained by the method of interpolation from the equivalent atomic number (Z_{eq}), to calculate the buildup factors. Computations are illustrated step by step as follows: (a) Calculation of the equivalent atomic number (Z_{eq}); (b) Calculation of geometric progression (G-P) fitting parameters; (c) Calculation of energy absorption and exposure buildup factors.

At the first step, the equivalent atomic number (Z_{eq}) for a particular material has been calculated by matching the ratio, $(\mu/\rho)_{Compton}/(\mu/\rho)_{Total}$ of that material at a specific energy with the corresponding ratio of an element at the same energy. Thus, firstly the Compton partial mass attenuation coefficient, $[(\mu/\rho)_{Compton}]$ and the total mass attenuation coefficients, $[(\mu/\rho)_{Total}]$ were obtained for the elements of Z = 4-40 and for the chosen materials in the energy region 0.015-15 MeV, using the WinXCom computer program [9] (initially developed as XCOM [10]). For the interpolation of Z_{eq} for which the ratio $(\mu/\rho)_{Compton}/(\mu/\rho)_{Total}$ lies between two successive ratios of elements, the following formula has been employed:

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

where Z_1 and Z_2 are the atomic numbers of elements corresponding to the ratios R_1 and R_2, respectively, R is the ratio for the chosen building materials at a specific energy.

At the second step, to calculate the geometric progression fitting parameters a similar interpolation procedure was adopted as in the case of the equivalent atomic number. The geometric progression fitting parameters for elements were taken from the ANSI/ANS-6.4.3 standard reference database, which provides the geometric progression fitting parameters for elements from beryllium to iron in the energy region 0.015-15 MeV up to 40 mfp.

Finally, these parameters were used to calculate the energy absorption and exposure buildup factors from the geometric progression fitting formula [6]:

$$B(E,X) = 1 + \frac{b-1}{K-1}(K^X - 1) \text{ for } K \neq 1 \quad (2)$$

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

where,

$$K(E,x) = cx^a + d\frac{\tan h\,(x/X_k - 2) - \tan h\,(-2)}{1 - \tan h\,(-2)}$$
$$\text{for } x \leq 40 \text{ mfp} \quad (4)$$

where E is the incident photon energy, X is the penetration depth in mfp, a,b,c,d and X_k are the geometric progression fitting parameters and b is the value of buildup factor at 1 mfp. The parameter K represents the photon dose multiplication and the change in the shape of the spectrum.

The mean free path (mfp), or relaxation length, is the quantity:P

$$x = 1/\mu \quad (5)$$

where μ is linear attenuation coefficient (cm^{-1}). This is the average distance of a single particle travels through a given attenuating medium before interacting. It is also the depth to which a fraction 1/e (about 37 %) of a large homogeneous population of particles in a beam can penetrate. For example, a distance of three free mean paths, 3/μ, reduces the primary beam intensity to 5 % [11].

RESULTS AND DISCUSSION

The chemical name and formula of the some vitamins are listed in Table-1. Table-2 gives the equivalent atomic numbers of the vitamins in the energy region of 0.015-15 MeV. The

TABLE-1
CHEMICAL FORMULA OF VITAMINS

Name		Chemical formula
Biotin	Vitamin B7	$C_{10}H_{16}N_2O_3S$
Flavonoid	Vitamin P	$C_{28}H_{34}O_{15}$
Retinol	Vitamin A	$C_{20}H_{30}O$
β-Carotene	Provitamin-A	$C_{40}H_{56}$
Riboflavin	Vitamin B2	$C_{17}H_{20}N_4O_6$
Folic acid	Vitamin B9	$C_{19}H_{19}N_7O_6$
Cyanocobalamin	Vitamin B12	$C_{63}H_{88}CoN_{14}O_{14}P$
Ascorbic acid	Vitamin C	$C_3H_4O_3$
α-Tocopherol	Vitamin E	$C_{29}H_{50}O_2$
Niacinamide	Vitamin B3	$C_6H_5NO_2$
Phylloquinone	Vitamin K1	$C_{31}H_{46}O_2$

exposure and energy absorption geometric progression fitting parameters for cobalamin (vitamin B12, $C_{63}H_{88}N_{14}O_{14}PCo$) have been given in Table-3 as an example. The energy absorption (EABF) and exposure (EBF) buildup factors have been shown in graphical form at fixed energy values [Figs. 1(a-c) and 2(a-c)] as well as at fixed penetration depths [Figs. 3(a-d) and 4(a-d)]. Also, Fig. 5(a,b) show the significant differences between the energy absorption and exposure buildup factors for selected compounds of maximum and minimum Z_{eq}. The energy dependence of EABF and EBF are discussed in the following paragraphs.

Standardization of the calculation: The present method was checked by calculating buildup factors for air in the energy

TABLE-2
EQUIVALENT ATOMIC NUMBERS OF THE VITAMINS FOR THE ENERGY RANGE 0.015-15 MeV

Energy (MeV)	A	B	C	D	E	F	G	H	I	J	K
0.015	9.055	6.748	5.777	5.619	6.600	6.621	9.877	7.076	5.789	6.624	5.827
0.020	9.164	6.760	5.790	5.622	6.607	6.625	10.136	7.093	5.805	6.628	5.843
0.030	9.304	6.768	5.800	5.618	6.606	6.622	10.473	7.107	5.820	6.624	5.858
0.040	9.387	6.774	5.806	5.619	6.606	6.620	10.688	7.112	5.829	6.623	5.867
0.050	9.442	6.778	5.812	5.620	6.607	6.620	10.847	7.115	5.836	6.624	5.873
0.060	9.483	6.782	5.816	5.622	6.610	6.622	10.970	7.118	5.840	6.626	5.878
0.080	9.544	6.788	5.821	5.625	6.613	6.625	11.158	7.122	5.848	6.629	5.884
0.100	9.585	6.792	5.825	5.626	6.617	6.628	11.237	7.125	5.852	6.632	5.888
0.150	9.649	6.799	5.829	5.629	6.622	6.632	11.410	7.130	5.857	6.637	5.893
0.200	9.688	6.799	5.832	5.631	6.622	6.632	11.515	7.129	5.860	6.637	5.896
0.300	9.731	6.805	5.835	5.632	6.626	6.636	11.644	7.134	5.864	6.641	5.900
0.400	9.750	6.807	5.837	5.633	6.628	6.637	11.716	7.135	5.866	6.642	5.902
0.500	9.764	6.808	5.838	5.634	6.628	6.637	11.756	7.135	5.867	6.643	5.903
0.600	9.773	6.809	5.839	5.634	6.629	6.638	11.782	7.136	5.868	6.643	5.904
0.800	9.781	6.809	5.839	5.634	6.629	6.638	11.806	7.136	5.869	6.644	5.904
1.000	9.780	6.809	5.839	5.634	6.629	6.638	11.808	7.136	5.869	6.643	5.904
1.500	7.356	6.249	5.178	5.077	6.150	6.241	7.465	6.637	5.121	6.242	5.228
2.000	7.159	6.228	5.161	5.062	6.130	6.225	6.965	6.618	5.102	6.226	5.211
3.000	7.116	6.223	5.157	5.058	6.126	6.221	6.860	6.614	5.097	6.223	5.206
4.000	7.101	6.219	5.153	5.054	6.123	6.219	6.831	6.611	5.093	6.220	5.203
5.000	7.093	6.219	5.153	5.055	6.122	6.219	6.818	6.610	5.093	6.220	5.203
6.000	7.088	6.218	5.152	5.054	6.121	6.218	6.809	6.609	5.092	6.219	5.202
8.000	7.083	6.215	5.150	5.052	6.119	6.217	6.800	6.607	5.089	6.218	5.200
10.000	7.080	6.214	5.151	5.053	6.117	6.216	6.795	6.607	5.090	6.217	5.201
15.000	7.067	6.213	5.147	5.047	6.118	6.217	6.783	6.604	5.084	6.217	5.197

A = Biotin; B = Flavonoid; C = Retinol; D = β-Carotene; E = Riboflavin; F = Folic acid; G = Cyanocobalamin; H = Ascorbic acid; I = α-Tocopherol; *J* = Niacinamide; K = Phylloquinone

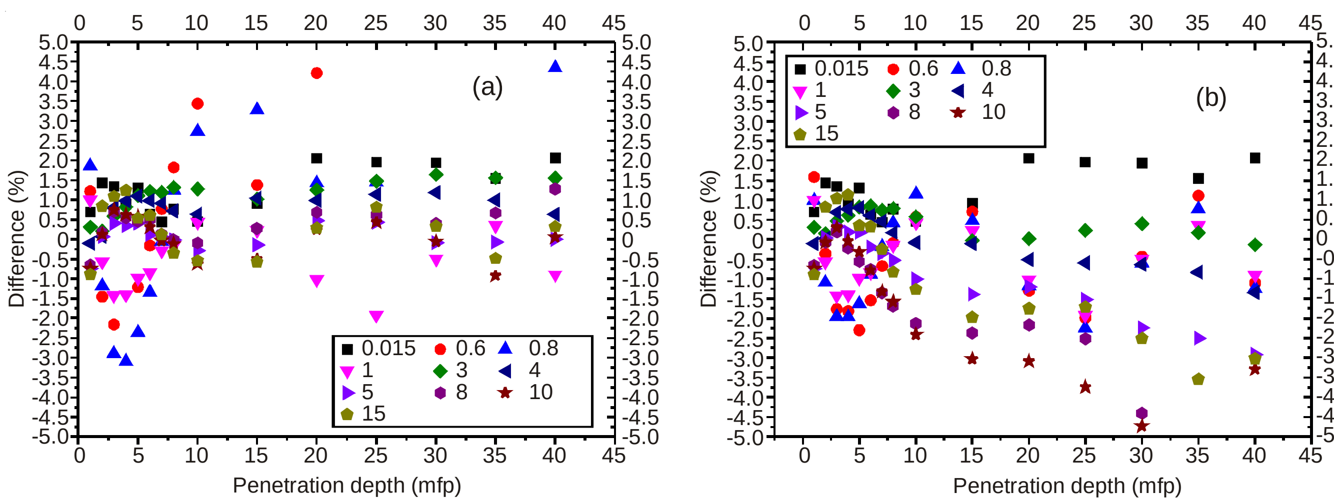

Fig. 1. Difference (%) between ANSI data base and present work with respect to the calculated values of EABF and EBF for air at some energies upto 40 mfp

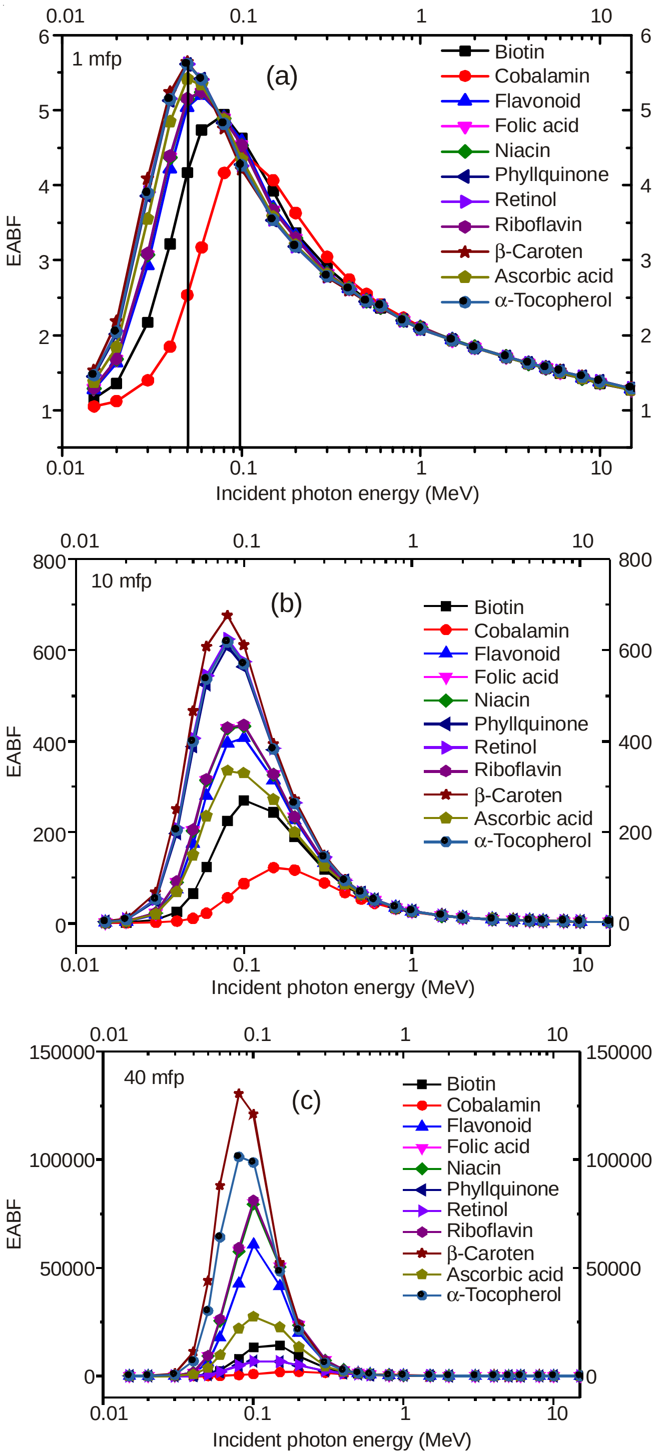

Fig. 2. Energy absorption buildup factor for vitamins in the energy region 0.015-15 MeV at 1, 10 and 40 mfp

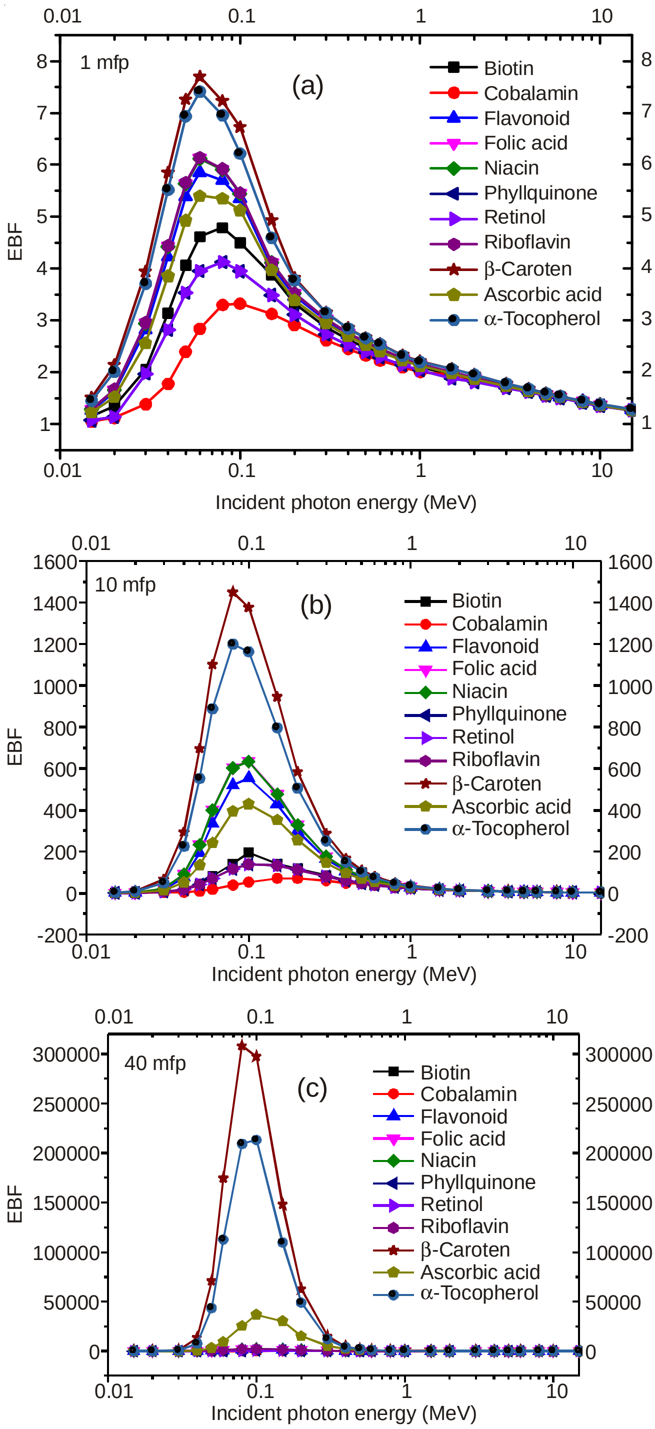

Fig. 3. Exposure buildup factor for vitamins in the energy region 0.015-15 MeV at 1, 10 and 40 mfp

range 0.015-15 MeV and penetration depth up to 40 mfp. The results so obtained were compared with standard energy absorption and exposure buildup factors data of the American National Standards [12] for some randomly selected energy between 0.015 and 15.0 MeV [13]. It can be seen from Fig. 6 that the energy absorption and exposure buildup factors generated by the present method are in excellent agreement with the standard data. This gives confidence in our results for the vitamins.

Energy absorption and exposure build up factor

Dependence of EABF and EBF on incident photon energy: Figs. 1(a-c) and 2(a-c) show the variations of energy absorption and exposure buildup factors with incident photon energy for all the selected vitamins at 1, 10 and 10 mean free path, respectively. It has been observed that despite of different equivalent atomic numbers of the vitamins, the vitamins shows almost similar trend with the increase in incident photon energy and for all the vitamins buildup factors values are small at lower energies of incident photon besides that higher

TABLE-3
GEOMETRIC PROGRESSION EXPOSURE AND ENERGY ABSORPTION BUILDUP FACTOR COEFFICIENTS FOR $C_{63}H_{88}CoN_{14}O_{14}P$ IN THE ENERGY RANGE 0.015-15 MeV

Energy (MeV)	EABF					EBF				
	a	b	c	d	Xk	a	b	c	d	Xk
0.015	0.197	1.051	0.409	-0.091	11.440	0.223	1.052	0.379	-0.114	11.690
0.020	0.202	1.121	0.410	-0.110	14.550	0.212	1.122	0.398	-0.114	13.540
0.030	0.180	1.401	0.472	-0.094	14.690	0.176	1.388	0.480	-0.092	14.600
0.040	0.114	1.849	0.629	-0.059	16.170	0.099	1.779	0.662	-0.047	16.410
0.050	0.088	2.535	0.737	-0.062	14.980	0.087	2.394	0.740	-0.055	14.310
0.060	0.033	3.171	0.922	-0.030	14.390	0.038	2.836	0.910	-0.033	13.270
0.080	-0.038	4.169	1.220	0.006	11.660	-0.028	3.300	1.183	-0.002	13.570
0.100	-0.071	4.448	1.405	0.021	13.178	-0.055	3.318	1.333	0.007	13.846
0.150	-0.115	4.067	1.671	0.043	13.424	-0.086	3.123	1.524	0.020	14.865
0.200	-0.123	3.632	1.731	0.045	13.732	-0.095	2.909	1.579	0.023	15.345
0.300	-0.123	3.044	1.726	0.044	14.066	-0.098	2.619	1.587	0.024	15.323
0.400	-0.115	2.742	1.663	0.039	14.410	-0.095	2.449	1.553	0.024	15.350
0.500	-0.108	2.548	1.605	0.037	14.395	-0.091	2.323	1.542	0.025	15.731
0.600	-0.100	2.413	1.549	0.034	14.575	-0.086	2.227	1.503	0.024	15.309
0.800	-0.086	2.235	1.452	0.030	14.827	-0.076	2.103	1.463	0.023	15.553
1.000	-0.075	2.114	1.379	0.027	15.069	-0.069	2.007	1.392	0.023	15.691
1.500	-0.058	1.936	1.269	0.024	14.346	-0.057	1.949	1.267	0.024	14.271
2.000	-0.039	1.835	1.175	0.017	13.968	-0.040	1.859	1.176	0.017	13.951
3.000	-0.012	1.708	1.056	0.004	12.764	-0.014	1.722	1.129	0.004	13.691
4.000	0.006	1.628	0.981	-0.001	14.082	0.004	1.634	0.988	-0.007	17.230
5.000	0.019	1.566	0.933	-0.013	13.772	0.017	1.564	0.939	-0.012	13.819
6.000	0.020	1.499	0.928	-0.016	16.371	0.029	1.518	0.902	-0.017	12.800
8.000	0.038	1.430	0.871	-0.022	12.053	0.033	1.426	0.883	-0.019	12.686
10.000	0.038	1.366	0.867	-0.022	14.328	0.037	1.363	0.869	-0.021	13.851
15.000	0.048	1.274	0.838	-0.034	15.185	0.047	1.272	0.841	-0.033	15.086

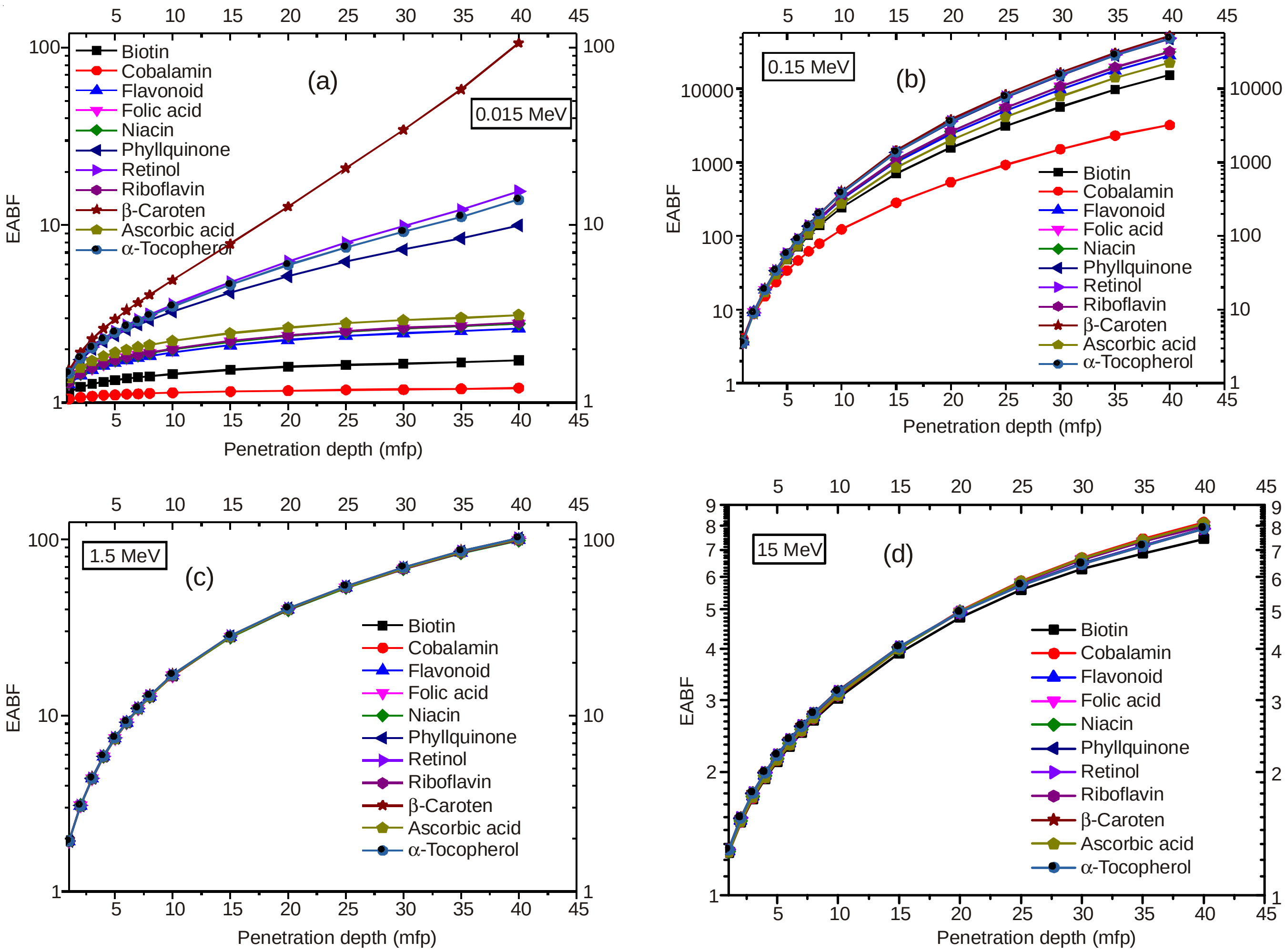

Fig. 4. Energy absorption buildup factor for vitamins up to 40 mfp at 0.015, 0.15, 1.5 and 15 MeV

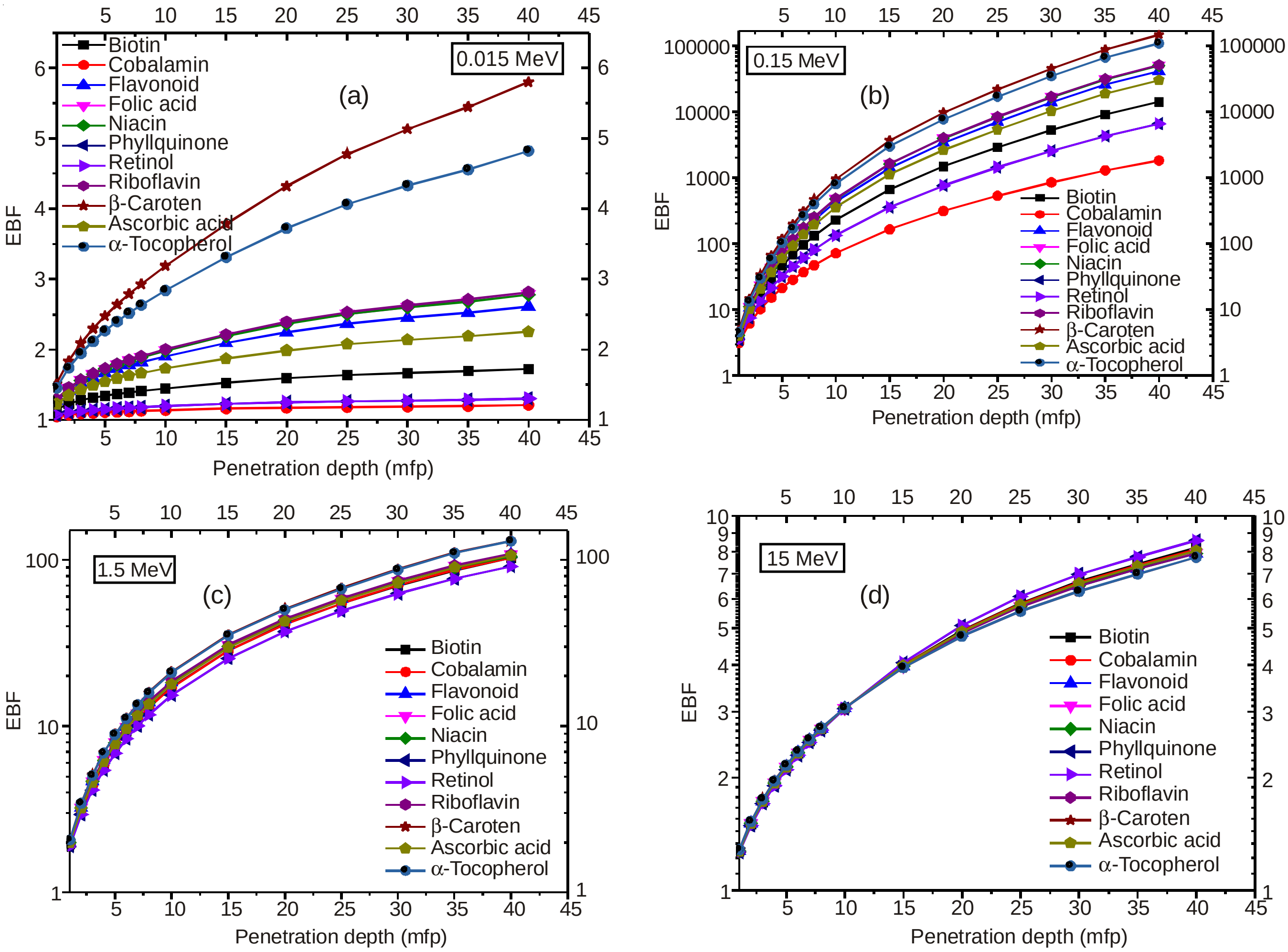

Fig. 5. Exposure buildup factor for vitamins up to 40 mfp at 0.015, 0.15, 1.5 and 15 MeV

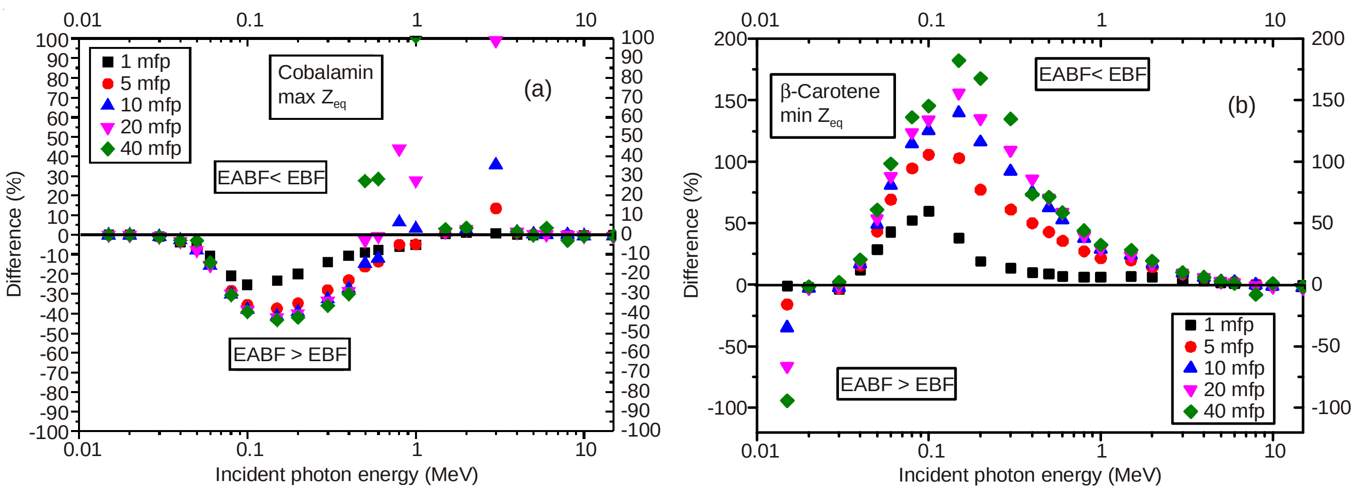

Fig. 6. Difference (%) between EABF and EBF for cobalamin and β-carotene in the energy region 0.015-15 MeV upto 40 mfp

energies of incident photon and show maximum values in the moderate energy region. In the higher and lower energy region, photoelectric effect and pair production are the dominant process, respectively. Hence, they do not exist for a longer period of time, resulting in less buildup factor at lower and higher energy regions. Meanwhile the energy of the incident photon increases, Compton scattering process starts dominating. In this process, photons are not completely abolished but only their energies are reduced. They exist for a long time in the material. It results in multiple Compton scattering, which enhance the build-up factors to maximum in the energy range 0.05-1 MeV. The maximum values for EABF and EBF occur at 0.06 MeV for selected vitamins except biotin and cobalamin and at 0.1 MeV for biotin and cobalamin. The buildup factors values of vitamins are almost distinguishable except biotin and cobalamin owing to large range of atomic numbers of constituent elements at 1 mfp (Figs. 1 and 2). It is also seen in Figs. 1 and 2 that the EABF and EBF can take very high values at the larger penetration depth (10, 40 mfp) for vitamins which have an equivalent atomic number (Z_{eq}), in the range 5-7. On the other hand the buildup factors reaches a lower value for cobalamin and biotin. The smaller buildup factor can be associated with higher Z_{eq}, which is in the range 11-7 for vitamins. If buildup factors of antioxidant vitamins which are used radio protector (cobalamin, ascorbic acid, vitamin E and β-carotene) are compared between themselves, it is seen that the buildup of photons is less in cobalamin and ascorbic acid.

Dependence of EABF and EBF on penetration depth: Figs. 3 and 4 show the buildup factors of vitamins compared at the penetration depths 1, 10 and 40 mfp. In general buildup factors are largest for β-carotene and smallest for cobalamin at all the penetration depths. It is clarified by cobalamin being a high Z_{eq} compound however β-carotene is a low-Z_{eq} compound. At low energies, there is a significant variation of EABF and EBF for all vitamins. This may be elucidated by the fact that, at low-energy, the small values of buildup factors are due to dominance of photo-electric effect which results in the fast removal of low-energy photons thereby not allowing these photons to buildup in the medium [14]. Therefore EABF and EBF depends on chemical composition at incident photon energy 0.015 MeV and 0.15 MeV. In contrast at incident photon energies 1.50 MeV EABF and EBF values are almost independent of chemical composition of the vitamins. So the values of buildup factors vary inversely with values of Z_{eq}. For higher energies in the ranges 1.5- 3 MeV, the pair production process starts pre-dominating and results with an electron-positron pair. The positron is rapidly annihilated, creating another pair of 0.511 MeV photons. These secondary γ-photons to some extend compensate for the primary loss of photons [15]. At energies beyond 3 MeV, buildup factors increase with increasing Z_{eq} at penetration depths $15 < x < 40$. Because the pair production process continue pre-dominating again. For lower penetration depths, these particles may escape from the material or after multiple collisions within the material comes to rest and further annihilates. With the increase in penetration depth, these secondary γ-rays (as a result of annihilation) contribute to the rise in intensity of the primary γ-rays [16].

Comparison of EABF and EBF: Fig. 5(a-b) gives the relative differences (%) between EABF and EBF. The differences may help in estimation of the maximum radiation intensity occurs, whether at the surface of the sample or inside it. This means that in some cases the exposure could be higher than energy absorption or vice versa for any given vitamin. The maximum differences exist in the intermediate energy region where Compton scattering is the main photon interaction process thus leading to large buildup factor values of EBF and EABF [17]. The relative differences were calculated for the compounds showing the minimum and the maximum value of Z_{eq}, *i.e.* for β-carotene and cobalamin, respectively. Maximum differences up to 182 and 42 % observed for β-carotene and cobalamin, respectively. The absorption of photons in air is comparable with materials of low Z_{eq} and hereby the EBF values could be more than EABF (Fig. 5a). The value of Z_{eq} for air lies in the range of 7-8 whereas the Z_{eq} values of β-carotene and cobalamin are in the range of 5-5.6 and 6.7-11.8, respectively. Due to low Z_{eq}, absorption in air contributes much more to EBF rather than EABF (Fig. 5a). However, for cobalamin the absorption inside the medium is much more than the absorption in air. Wherefore higher Z_{eq} of cobalamin, EABF values higher than EBF in the energy regions where photons buildup more (Fig. 5b).

Conclusion

The geometric progression fitting formula has been used for calculating energy absorption and exposure buildup factors of vitamins in the energy range 0.015-15 MeV and penetration depths up to 40 mfp. The present work should be useful in radiation dosimetry and therapy. From the point of radio-protection, it has been concluded that for the lower energy region (< 1.5 MeV) and all the penetration depths cobalamin and biotin have the minimum buildup factors, respectively. For 15 MeV, Biotin and vitamin E have the minimum buildup factors. Due to buildup of cobalamin and ascorbic acid (vitamin C), antioxidant vitamins, are less they may be used as a radio protective.

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